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CHANNEL CONFIGURATION FOR PACKET RADIO SYSTEM

I. INTRODUCTION

In this note we compare six channel configurations for the packet radio system on the basis of channel utilization and delay. The ratio between the packet rate from station to terminals to the packet rate from terminals to station, α , is introduced as a parameter. The main question addressed is the following: Should one use separate channels, one for transmission from terminals to station and the second for transmission from station to terminals, or should one use a common channel for transmission in both directions ? The analysis demonstrates that if α is known accurately then one can obtain a higher maximum utilization by properly splitting the channel. However, when the system operates at lower values of utilization then the common channel is better in terms of average delay. Moreover, if α is not known (or varies) then the common chanel configuration is superior in terms of maximum utilization and delay. Thus dividing the channel into forward and backward subchannels does not seem advisable on the basis of utilization and delay. The following modes of channel access are also compared: slotted and non-slotted ALOHA [3], and carrier sense [2]. It is demonstrated, that carrier sense and slotted ALOHA are better than non-slotted ALOHA.

Curves of maximum utilization and expected delay for several values of parameter α are obtained. The equations used assume an idealized case as specified in the assumptions. This level of analysis is sufficient however for eliminating many configurations in an objective manner. Interesting characteristics of delay versus channel throughput and channel traffic are demonstrated.

The model used is that of a single station which communicates with a large number of terminals. This model seems to us fairly accurate for a suburban area in which one station is sufficient (in terms of distance and channel capacity) to handle all traffic for the area; it is a somewhat simplified model when considering communication in an urban area or in a rural area [1].

The channel configurations considered are the following:

2-N Separate channels for each direction. The capacities of the channels are equal. The channels are nonslotted and packets access the channel at random points in time (nonslotted ALOHA [3]). One channel is used for transmission from terminals to station, and the second channel for transmission from station to terminals.

1-N The channel is accessed in the same way as in configuration 2-N. In this case, however, the configuration consists of a single channel which is used for transmission in both directions.

2-S Two equal capacity channels, one for each direction. The channels are slotted with a slot time assumed equal to the packet transmission time. Packets access the channel at random slots in time (slotted ALOHA).

1-S A single slotted channel used for transmission in both directions.

2-C Two equal capacity channels, one for transmission in each direction. Packets from station to terminals access the channel at random points in time and there is no competition. From terminals to station the channel access is as following [2]: The device is sensing the channel for a constant period of 6 seconds to detect whether the channel is idle; if the channel is idle, the device transmits the packet; if the channel is busy, the device will wait until the channel becomes idle and only then it transmits the packet.

1-C A single channel is used for transmission in both directions. Packets from station to terminals and from terminals to station access the channel by first sensing it, as described above.

Notation

- A slot is defined to be the transmission time of a packet.

σ - rate of packet origination in packets per slot.

γ - rate of packet origination plus packet retransmission in packets per slot.

D - expected packet delay; from the time that the packet is ready for transmission by the originating device until the time that the last bit has been successfully received by the receiving device.

q - probability of successful transmission, i.e. the probability that no conflict with another packet has occurred.

A - the expected packet delay when no conflicts occur.

R - the expected waiting time before a packet is retransmitted, given the previous transmission of that packet has been blocked due to conflict.

k - number of slots of time over which retransmission is uniformly distributed after a constant period of waiting.

E - the expected number of retransmissions

δ - a constant time that the channel is sensed in configurations 2-C and 1-C.

a - ratio of packet origination rate from station to terminals to packet origination rate from terminals to station.

- subscript 1 will denote quantities from terminals to station, and subscript 2 quantities from station to terminals.

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Assumptions

1. The point process of packet origination and the point process of packet origination plus retransmission are both assumed Poisson.
2. The probability that a packet is blocked given the packet is new is assumed equal to the probability that the packet is blocked given it has been blocked before; both are assumed to be independent of k (see [4] and [5]).
3. To be compatible with the other configurations considered, we assume in the carrier sense channel access that the expected waiting time between retransmissions is the same as in the other configurations. Thus, the differences in delay are due to the expected number of retransmissions.
4. The constant time δ used for sensing the channel is assumed to be the propagation time between devices.
5. In evaluating the delays for configurations 1-N, 2-N, 1-S, 2-S, we assume that the propagation time P and the transmission time T satisfy $P \ll T$, thus P was ignored. The propagation time between devices, δ, is used only in configurations 2-C and 1-C for evaluating the probability of successful transmissions.
6. Packet transmission time T=1; thus δ is a fraction of the transmission time; g is also the utilization or throughput per slot;

and γ is also the channel traffic per slot. Note that in the equations we assume T=1 for the 2-channel as well as 1-channel configurations, for convenience. In drawing the delay curves, however, it is taken into account that the 2-channel configuration is a split of the 1-channel. Thus, assuming the same packet size, the transmission time in the 2-channel configuration is T=2. The number of slots delay is therefore normalized to the 1-channel configuration.

7. Although a ratio a is used, it is assumed that the process of packet origination from station to terminals is independent of the process of packet origination from terminals to station.

8. A no-capture system is assumed. That is, whenever two or more packets overlap, none of them is correctly received.

II. MAXIMUM UTILIZATION

It is demonstrated that no configuration is superior to all others for all values of α. Furthermore, if one assumes that a packet which originates from a terminal will always be directed towards a station then α has the practical meaning of the number of response packets for every originating packet. Thus the maximum utilization for each of the configurations is obtained as a function of α. The optimization problem is therefore the following: For some given configuration, given

$$\sigma_1 = \sigma_1(\gamma_1, \gamma_2, \delta) \tag{1}$$

$$\sigma_2 = \sigma_2(\gamma_1, \gamma_2, \delta) \tag{2}$$

Find the maximum of $(\sigma_1 + \sigma_2)$, subject to the constraints:

$$\alpha = \sigma_2/\sigma_1 \tag{3}$$

$$\gamma_2 \leq 1 \tag{4}$$

Note that the value of γ_1 is not restricted. This is because we assume an infinite number of terminals with an average origination rate per terminal which tends to zero. Also, it is assumed that

the terminal will keep on retransmitting the same packet until it is successfully received. Thus a packet from terminals to station does not encounter any queuing delay.

For configurations 2-N, 2-S, and 2-C, we have

$$\sigma_1 = \sigma_1(\gamma_1, \delta)$$

$$\sigma_2 = \gamma_2$$

and

$$\sigma = \sigma_1 + \sigma_2 = (1+\alpha)\ \sigma_1(\gamma_1, \delta)$$

Let σ_{1M} denote the maximum of σ_1, then for $\alpha\sigma_{1M} \leq 1$, $\sigma_M = (1+\alpha)\ \sigma_{1M}$. For $\alpha\sigma_{1M} > 1$ the channel from station to terminals is saturated and $\sigma_M = (1+\frac{1}{\alpha})$. Dividing by 2 to account for the fact of having two channels, we obtain:

$$\sigma_M = \begin{cases} \frac{1}{2}\ (1+\alpha)\ \sigma_{1M} & , \quad \text{for} \quad \alpha \leq 1/\sigma_{1M} \\ \\ \frac{1}{2}\ (\frac{1+\alpha}{\alpha}) & , \quad \text{for} \quad \alpha > 1/\sigma_{1M} \end{cases} \tag{5}$$

For the specific cases we have:

Configuration 2-N

$$\sigma_1^{2-N} = \gamma_1\ e^{-2\gamma_1}\ ;\ \sigma_2^{2-N} = \gamma_2\ ;\ \text{and}\ \ \sigma_{1M}^{2-N} = 1/2e$$

Thus:

$$\sigma_M^{2-N} = \begin{cases} \frac{1}{2}\ (\frac{1+\alpha}{2e})\ ; & \text{for} \quad \alpha \leq 2e \\ \\ \frac{1}{2}\ (\frac{1+\alpha}{\alpha})\ ; & \text{for} \quad \alpha > 2e \end{cases} \tag{6}$$

Configuration 2-S

$$\sigma_1^{2-S} = \gamma_1 e^{-\gamma_1} \; ; \quad \sigma_2^{2-S} = \gamma_2 \; ; \quad \text{and} \quad \sigma_{1M}^{2-S} = 1/e$$

Thus:

$$\sigma_M^{2-S} = \begin{cases} \frac{1}{2}\left(\frac{1+\alpha}{e}\right) \; ; & \text{for} \quad \alpha \leq e \\ \\ \frac{1}{2}\left(\frac{1+\alpha}{\alpha}\right) \; ; & \text{for} \quad \alpha > e \end{cases} \tag{7}$$

For all other configurations the optimization is done numerically since the derivations result in transcendental equations in γ. We write, however, the equations for σ_1 and σ_2 that were used.

Configuration 2-C[2]

$$\sigma_i^{2-C} = \frac{\gamma_1(1+\delta\gamma_1)\left[\gamma_1(1+\delta)+e^{-\delta\gamma_1}\right] e^{-\gamma_1(1+2\delta)}}{\gamma_1(1+2\delta)-(1-e^{-\delta\gamma_1})+(1+\delta\gamma_1)\, e^{-\gamma_1(1+\delta)}} \tag{8}$$

$$\sigma_2^{2-C} = \gamma_2$$

Configuration 1-N

$$\sigma_1^{1-N} = \gamma_1 e^{-2(\gamma_1+\gamma_2)} \tag{9}$$

$$\sigma_2^{1-N} = \gamma_2 e^{-2\gamma_1} \tag{10}$$

Configuration 1-S

$$\sigma_1^{1-S} = \gamma_1 e^{-(\gamma_1+\gamma_2)} \tag{11}$$

$$\sigma_2^{1-S} = \gamma_2 e^{-\gamma_1} \tag{12}$$

Configuration 1-C

$$\sigma_1^{1-C} = \frac{\gamma_1[1+\delta(\gamma_1+\gamma_2)]\left[(1+\delta)(\gamma_1+\gamma_2)+e^{-\delta(\gamma_1+\gamma_2)}\right] e^{-(1+2\delta)(\gamma_1+\gamma_2)}}{(1+2\delta)(\gamma_1+\gamma_2)-1+e^{-\delta(\gamma_1+\gamma_2)}+[1+\delta(\gamma_1+\gamma_2)]\, e^{-(1+\delta)(\gamma_1+\gamma_2)}} \qquad (13)$$

$$\sigma_2^{1-C} = \frac{\gamma_2(1+\delta\gamma_1)\left[(1+\delta)\gamma_1+e^{-\delta\gamma_1}\right] e^{-(1+2\delta)\gamma_1}}{(1+2\delta)\gamma_1-1+e^{-\delta\gamma_1}+(1+\delta\gamma_1)\, e^{-(1+\delta)\gamma_1}} \qquad (14)$$

Remark: If $e^{-\gamma_2}$ in (11) is approximated by $(1-\gamma_2)$ then a closed form optimum solution for σ_M in configuration 1-S can be obtained:

$$\sigma_M^{1-S} = \frac{(1+\alpha)(\sqrt{1+4\alpha}-1)}{\alpha(\sqrt{1+4\alpha}+1)} = \frac{1}{2\alpha}(\sqrt{1+4\alpha}-1) \qquad (15)$$

The values of γ_1 and γ_2 at the maximum utilization are given by

$$\gamma_1 = \frac{1}{2\alpha}(\sqrt{1+4\alpha}-1); \quad \gamma_2 = \frac{\sqrt{1+4\alpha}-1}{\sqrt{1+4\alpha}+1} \leq 1 \qquad (16)$$

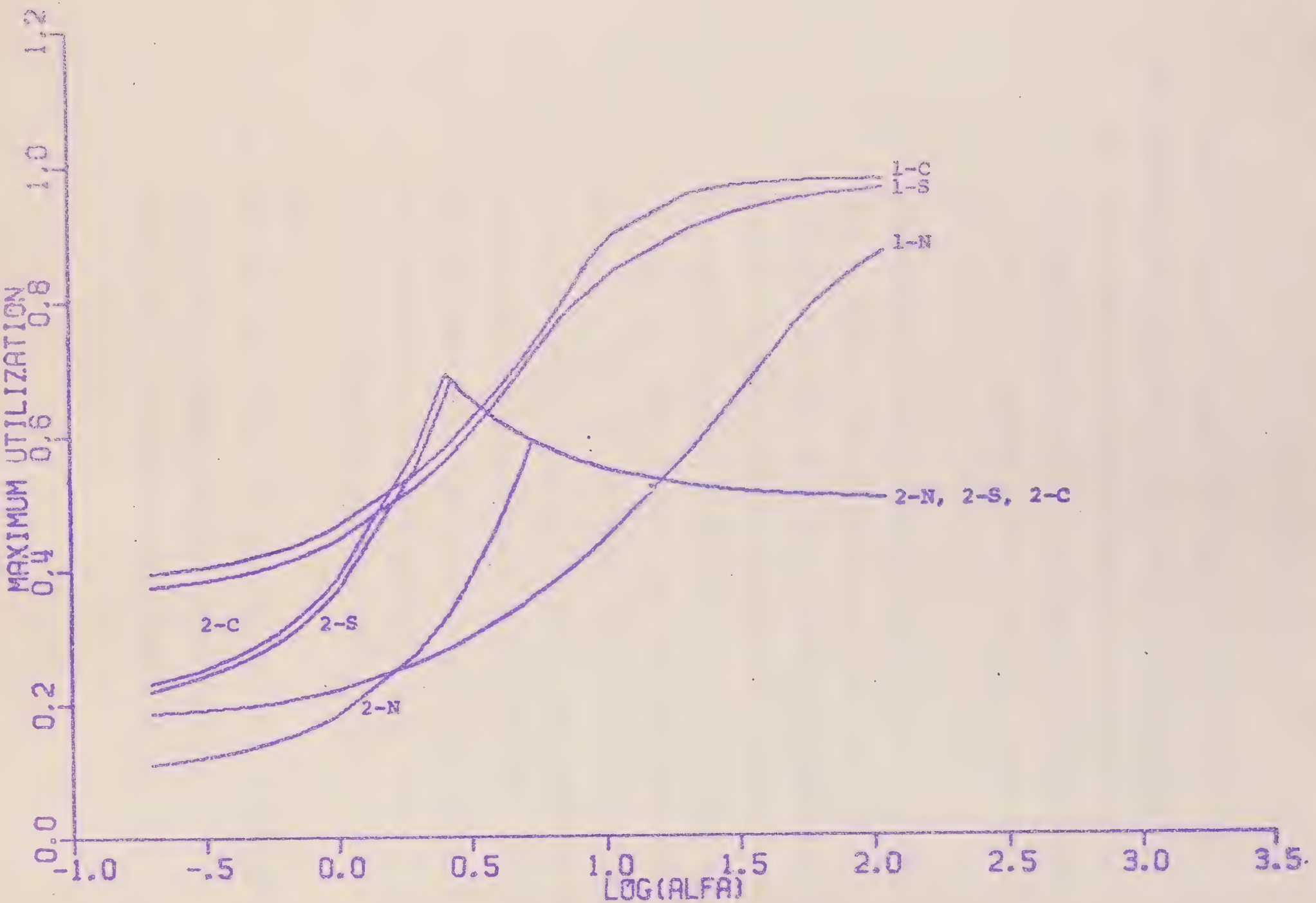

MAXIMUM UTILIZATION
0.0
0.2
0.4
0.6
0.8
1.0
1.2
-1.0
-.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
LOG(ALFA)
1-C
1-S
1-N
2-N, 2-S, 2-C
2-C
2-S
2-N

FIGURE 1

Figure 1 shows the maximum utilization versus α for the six configurations considered. We observe the following:

(1) The maximum utilization (throughput) which can be obtained depends upon α ; and there is no configuration which is uniformly better then all others for all values of α.

(2) Comparing a 2-channel versus 1-channel with the same mode of channel access; it is seen that there is an interval of α for which the 2-channel configuration is superior in terms of throughput to the 1-channel configuration; and outside of this interval the 1-channel is superior. This suggests that if α is known with certainty, then one can always design a 2-channel configuration which results in a higher maximum throughput than a common channel configuration with the same mode of access.

(3) For the modes of channel access considered, when $\alpha > 2e$ then the maximum utilization which can be obtained by any of the configurations 1-N, 2-S, and 2-C is the same.

(4) In the limit, when $\alpha \to \infty$ then the maximum utilization of all the 2-channel configurations tend to .5 and those of the 1-channel configurations tend to 1.

III. DELAY CONSIDERATIONS

The delay that a packet from terminal to station encounters is the transmission delay plus the delay due to waiting and retransmission when conflicts with other packets occur. A packet from station to terminal encounters the delay described above plus queuing delay at the station. When writing the queuing delay we assume that packets arrive according to a Poisson distribution and require constant service time equal to the transmission time T=1 (an M/D/1 queuing system). The retransmission mechanism for all the configurations was taken to be the same and is the following: the device waits for a period 2T (T for transmission and T for a possible acknowledgment) and retransmits the packet after an additional random amount of time uniformly distributed over kT slots.

Give one of the configurations, the average delay from terminals to station, D_1, and from station to terminals, D_2, can be written as:

$$D_1 = A_1 + R_1 E_1$$

$$D_2 = A_2 + R_2 E_2$$

where A is the expected delay when no conflict occurs, R is the expected waiting time before each retransmission and E is the expected number of retransmissions. The expected delay for an average packet in the system is:

$$D = \frac{\sigma_1}{\sigma} D_1 + \frac{\sigma_2}{\sigma} D_2 = \frac{1}{1+\alpha} D_1 + \frac{\alpha}{1+\alpha} D_2 \qquad (17)$$

Note that for any of the two channel configurations we have $\sigma_2 = \gamma_2$. That is, Pr[successful transmission] = 1 and thus $E_2 = 0$. Therefore, no retransmission is necessary and the delay is due to the packet queuing and transmission time.

We now write D_1 and D_2 for each of the configurations considered. We denote by $\bar{K} = \frac{k}{2} + 2 = R$, and use the assumptions 2, 3, and 5, of Section I. Furthermore, the ratio α is always preserved. See in particular assumption 5.

Configuration 2-N

$$D_1^{2-N} = 1 + \bar{K} \frac{1-e^{-2\gamma_1}}{e^{-2\gamma_1}} \qquad (18)$$

$$D_2^{2-N} = 1 + \frac{\alpha\gamma_1 e^{-2\gamma_1}}{2(1-\alpha\gamma_1 e^{-2\gamma_1})} \qquad (19)$$

Configuration 2-S

$$D_1^{2-S} = 1.5 + \bar{K} \frac{1-e^{-\gamma_1}}{e^{-\gamma_1}} \qquad (20)$$

$$D_2^{2-S} = 1 + \frac{\alpha\gamma_1 e^{-\gamma_1}}{2(1-\alpha\gamma_1 e^{-\gamma_1})} + \tfrac{1}{2}(1-\alpha\gamma_1 e^{-\gamma_1}) \qquad (21)$$

The last term in (21) is due to waiting for the beginning of a slot when the channel is idle and when slots are assumed to be assigned by an external clock. The additional delay of .5 in (20) is also due to waiting for the beginning of a slot; however, the terminal always considers the channel to be idle.

Configuration 2-C

$$D_1 = 1 + \delta + \bar{k} \frac{\gamma_1 - \sigma_1^{2-C}}{\sigma_1^{2-C}} \tag{22}$$

$$D_2 = 1 + \frac{\alpha\sigma_1^{2-C}}{2(1-\alpha\sigma_1^{2-C})} \tag{23}$$

where σ_1^{2-C} is given by Eq. (8).

Configuration 1-N

$$D_1^{1-N} = 1 + \bar{k} \frac{1-e^{-2(\gamma_1+\gamma_2)}}{e^{-2(\gamma_1+\gamma_2)}} \tag{24}$$

$$D_2^{1-N} = 1 + \bar{k} \frac{1-e^{-2\gamma_1}}{e^{-2\gamma_1}} + \frac{\gamma_2}{2(1-\gamma_2)} \tag{25}$$

Configuration 1-S

$$D_1^{1-S} = 1.5 + \bar{k}\,\frac{1-e^{-(\gamma_1+\gamma_2)}}{e^{-(\gamma_1+\gamma_2)}} \tag{26}$$

$$D_2^{1-S} = 1 + \bar{k}\,\frac{1-e^{-\gamma_1}}{e^{-\gamma_1}} + \frac{\gamma_2}{2(1-\gamma_2)} + \tfrac{1}{2}(1-\gamma_2) \tag{27}$$

Configuration 1-C

$$D_1^{1-C} = 1 + \delta + \bar{k}\,\frac{\gamma_1 - \sigma_1^{1-C}}{\sigma_1^{1-C}} \tag{28}$$

$$D_2^{1-C} = 1 + \delta + \bar{k}\,\frac{\gamma_2 - \alpha\sigma_1^{1-C}}{\alpha\sigma_1^{1-C}} + \frac{\gamma_2}{2(1-\gamma_2)} \tag{29}$$

where σ_1^{1-C} is given by Eq. (13)

The delay equations are investigated by increasing the channel traffic γ_1 and requiring that the station respond with α packets for each packet that it correctly receives. This approach seems natural since it implies that the demand for the communication system originates from the user (the terminals). Furthermore, we note that initially one cannot

control the amount of traffic that is generated by the "infinite" number of terminals.

All the curves were drawn using the retransmission parameter $K = 4$. In the carrier-sense mode of channel access we used $\delta = 0.2$.

For a given parameter α we obtained the following curves: delay versus throughput (σ), delay versus channel traffic γ_1, and for each configuration we obtain D_1, D_2 and D versus channel traffic γ_1. Figures 2, 4, and 6, show the delay versus throughput for each of the six configurations for $\alpha = 0.5$, 2.0, and 10.0, respectively. Figures 3, 5, and 7, show the delay versus channel traffic γ_1 for the six configurations, for the corresponding values of α. The delays of a packet from terminals to station, D_1, from station to terminals, D_2, and the average, D, for each of the configurations versus γ_1 are shown in Appendix A for $\alpha = 0.5$, in Appendix B for $\alpha = 2.0$, and in Appendix C for $\alpha = 10.0$. Note that the delays are normalized to the number of slots, where a slot is the transmission time of a packet in the 1-channel configuration. Thus the delays can be compared. The channel traffic γ_1, however, is the rate per slot.

Observations and Discussion

Interesting phenomena which are not common in point-to-point communication networks, such as the ARPANET, can be observed. Some of these are due to the natural elimination process as a result of collisions when a channel is accessed at random in a broadcasting mode, and others because of the constant a that was assumed.

In Figures 2 and 4, one can see that when γ_1 increases beyond a certain value then the utilization of the system decreases whereas the delay increases. This is due to the fact that when γ_1 is increased (beyond a certain value) then the number of conflicts increases and the number of packets correctly received by the station decreases. The highest value of throughput for each of the configurations is also seen in these curves and can be compared with Figure 1. The particular value of γ_1 at which the maximum utilization is obtained can be taken from the corresponding figures of delay versus γ_1.

The delay from terminals to station does not go to infinity for finite values of γ_1 and γ_2. Thus, whenever the delay goes to infinity it is due to the queuing delay at the station when γ_2 approaches unity. In particular, consider any of the 2-channel configurations, and

let σ_{1M} denote the maximum utilization from terminals to station, then the delay will be finite for all a for which $a\sigma_{1M} < 1$. This can be observed in Figures 2 and 4, where the delay is finite for the three cases 2-N, 2-S, 2-C. On the other hand, in Figure 6 where $a = 10.0$, these delays go to infinity. It is interesting to note that the maximum throughput is obtained at a finite delay when $a\sigma_{1M} < 1$.

In the curves given in the Appendices for the 2-channel configurations one can observe that the delay from station to terminals as a function of γ_1 has a maximum value at the point γ_1 at which σ_{1M} is obtained. In Figure C-2-N in Appendix C one can see that D_2 increases to infinity and then becomes finite again when γ_1 is such that $10.x\,\sigma_1 < 1$. This is also seen in Figures 6 and 7.

To explain in more detail why the curves intersect each other, consider Figure 2 which is the case for $a = 0.5$. Also note the functions σ_1 versus γ_1 in Figure 8 for the channel from terminals to station. The fact $a\sigma_{1M} < 1$ for all three modes of channel access explains the order of the maximum throughputs. To explain the intersection between 2-S and 2-C in Figure 2, note in Figure 8 the intersection between σ_1^{2-S} and σ_1^{2-C}. For the interval $\gamma_1 \leq \gamma_1^0$, $\sigma_1^{2-C} \geq \sigma_1^{2-S}$. Therefore $\sigma^{2-C} \geq \sigma^{2-S}$

for some given delay. The opposite is true for $\gamma_1 > \gamma_1^0$. A similar explanation holds for the fact that 1-S and 1-C intersect each other. Simply put, it means that when the channel traffic is high it is useless to sense the carrier since if the channel is busy there is a high probability that more packets will arrive during the busy period and thus will result in a conflict upon transmission. On the other hand, if the channle is idle then the device wasted a waiting period of δ and thus increases its probability of conflict.

Also note that curve 1-N intersects many other curves in figure 2. The reason is that when the channel traffic is low the probability of conflict is low and thus the waiting period of δ in the carrier sense channel access and an average of ½ slot in the slotted case are wasted.

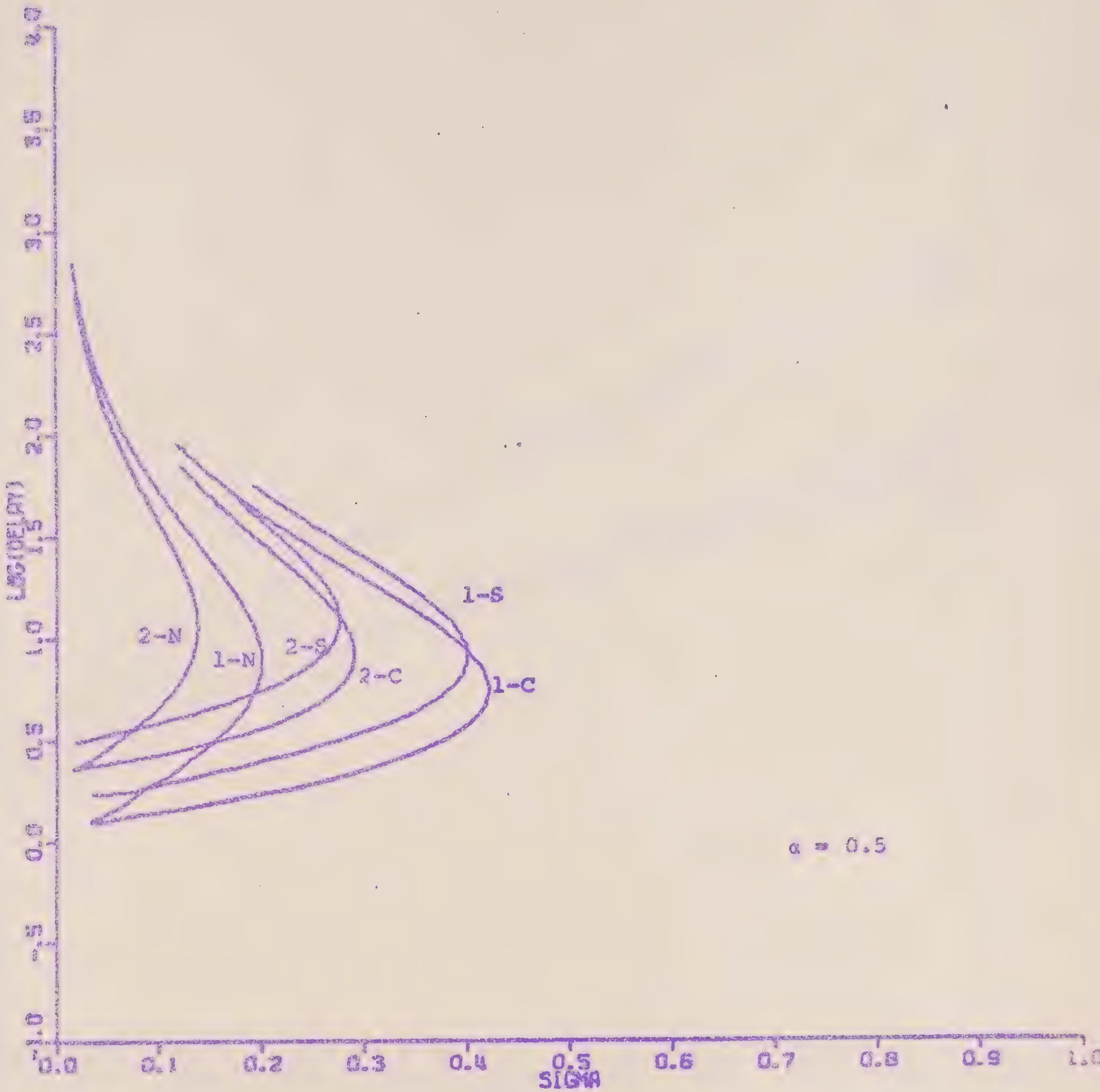


FIGURE 2

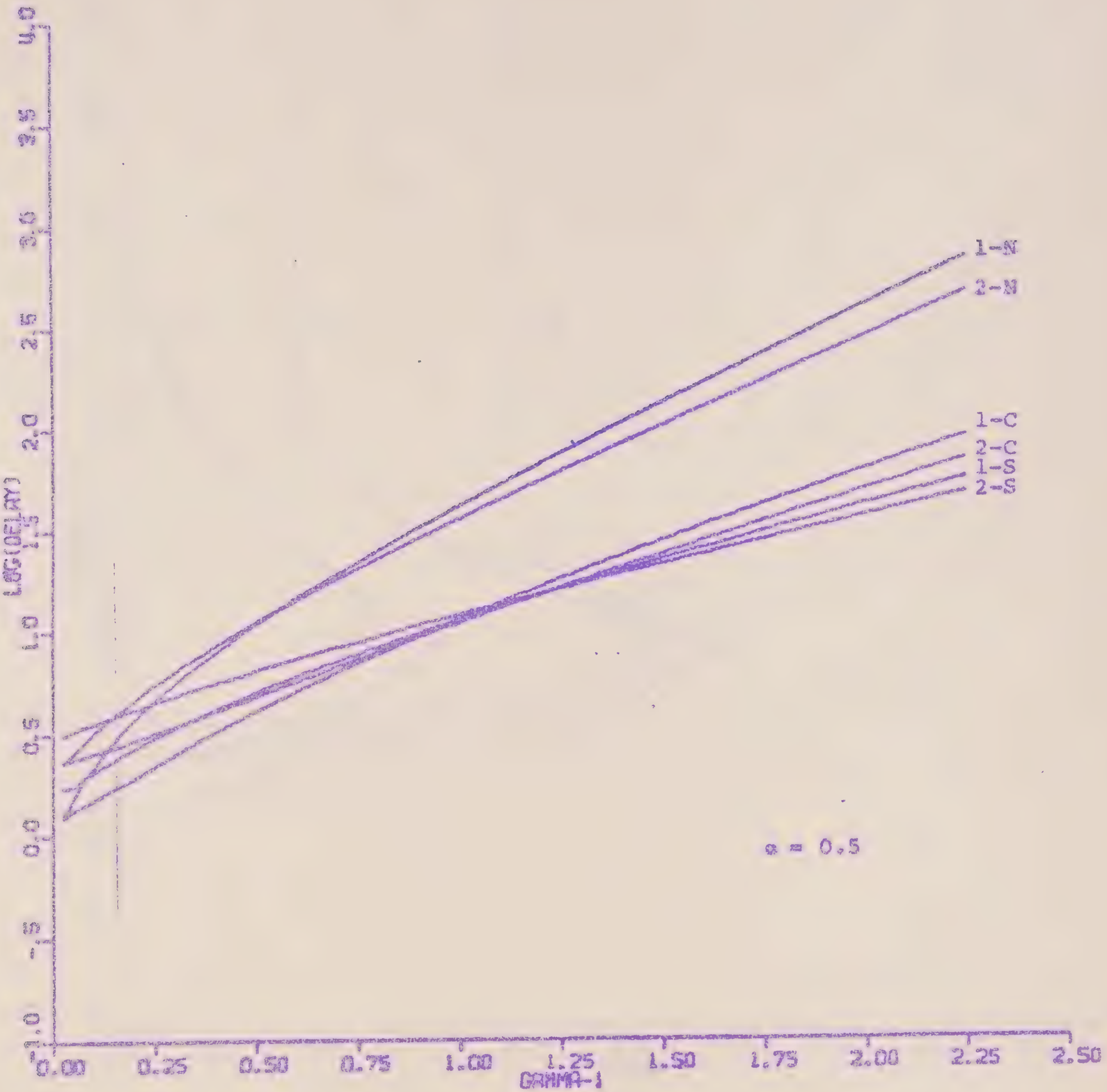

LOG(OFLAY)
-.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
GAMMA-1
1-N
2-N
1-C
2-C
1-S
2-S
α = 0.5

FIGURE 3

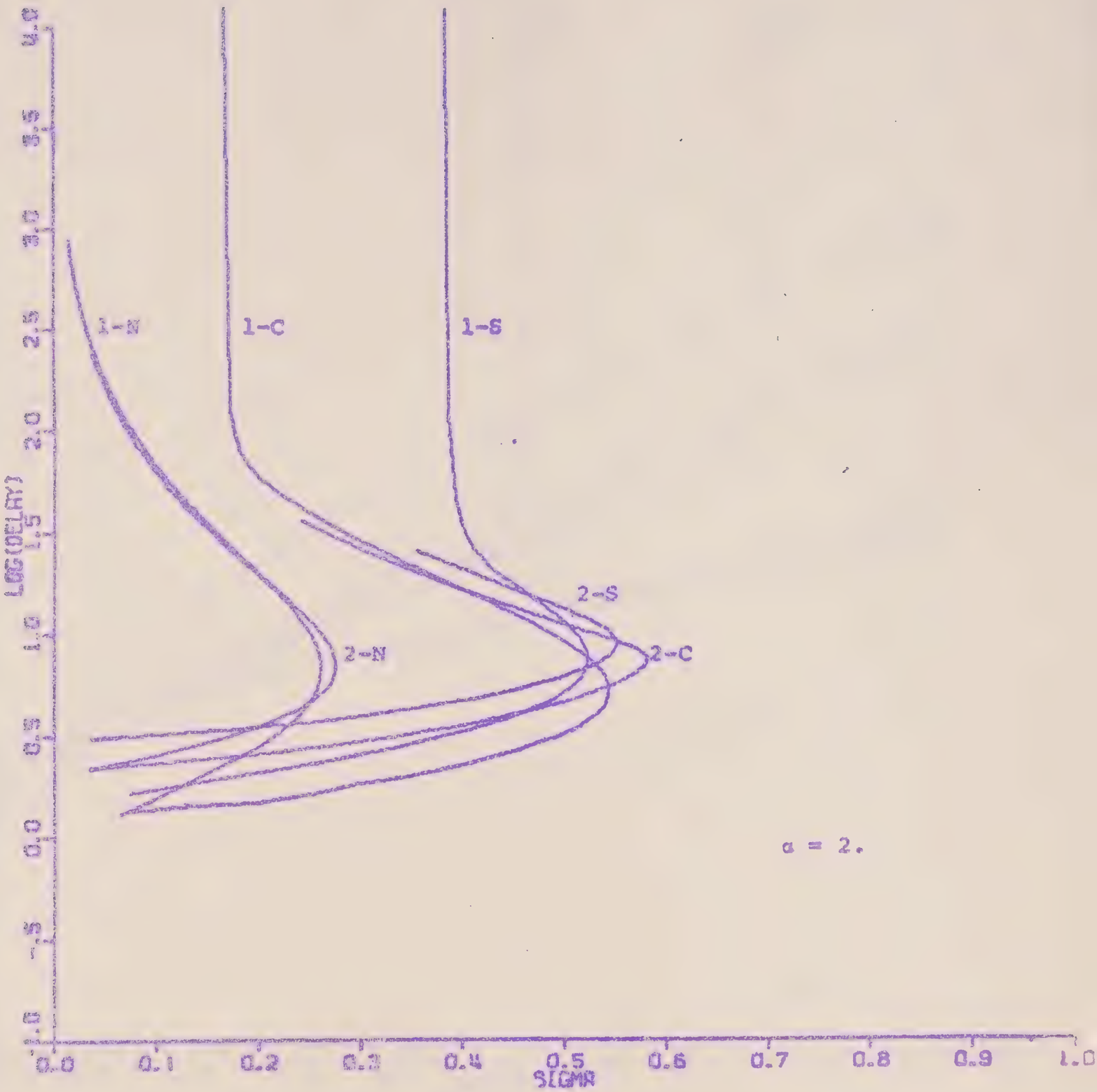


FIGURE 4

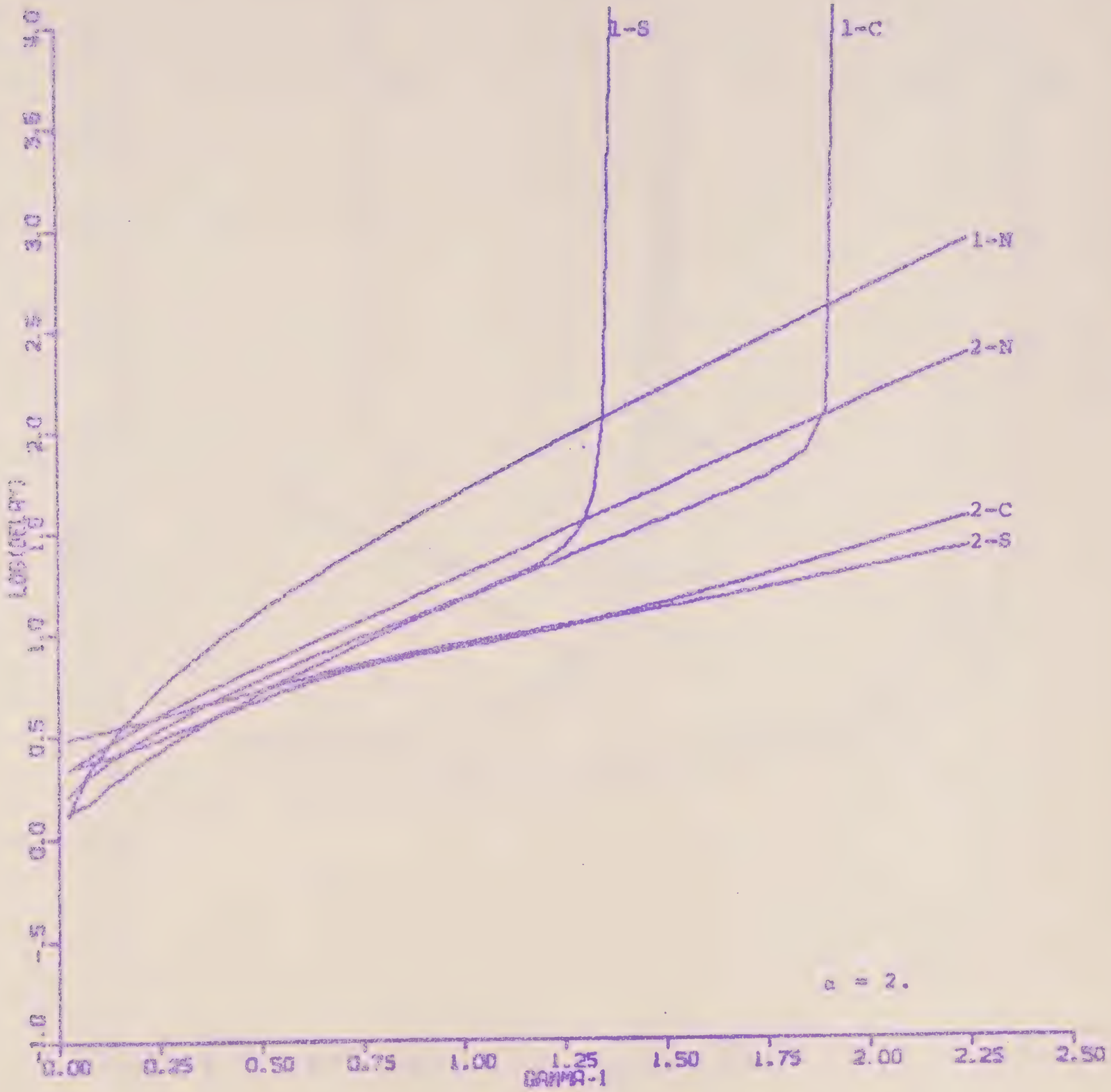

1-S
1-C
1-N
2-N
2-C
2-S
α = 2.
LOG(DELAY)
GAMMA-1
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
-1.0
-.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

FIGURE 5

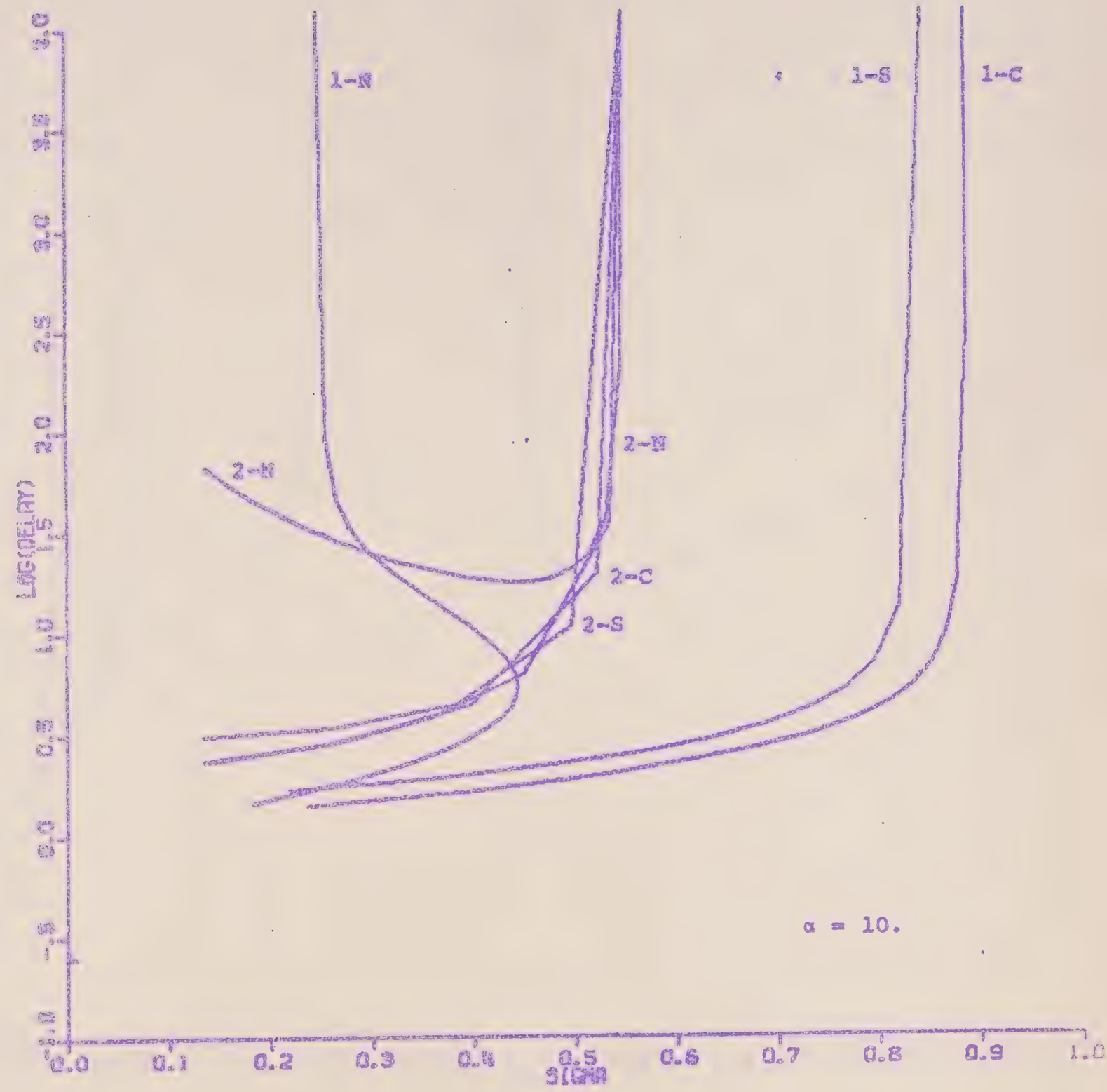

1-N
1-S
1-C
2-N
2-N
2-C
2-S
LOG(DELAY)
SIGMA
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
α = 10.

FIGURE 6

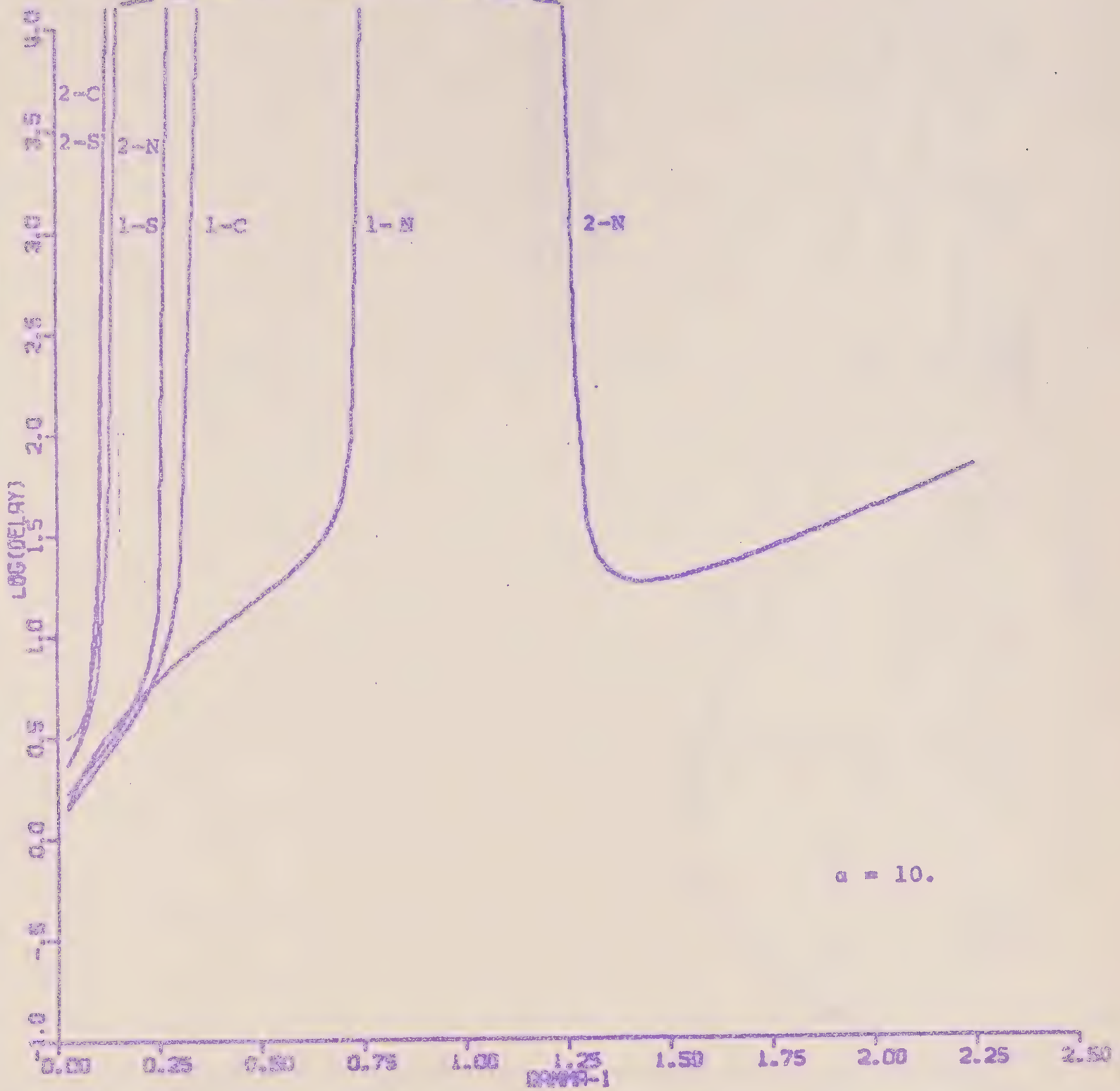

2-C
2-S
2-N
1-S
1-C
1-N
2-N
LOG(DELAY)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
a = 10.

FIGURE 7

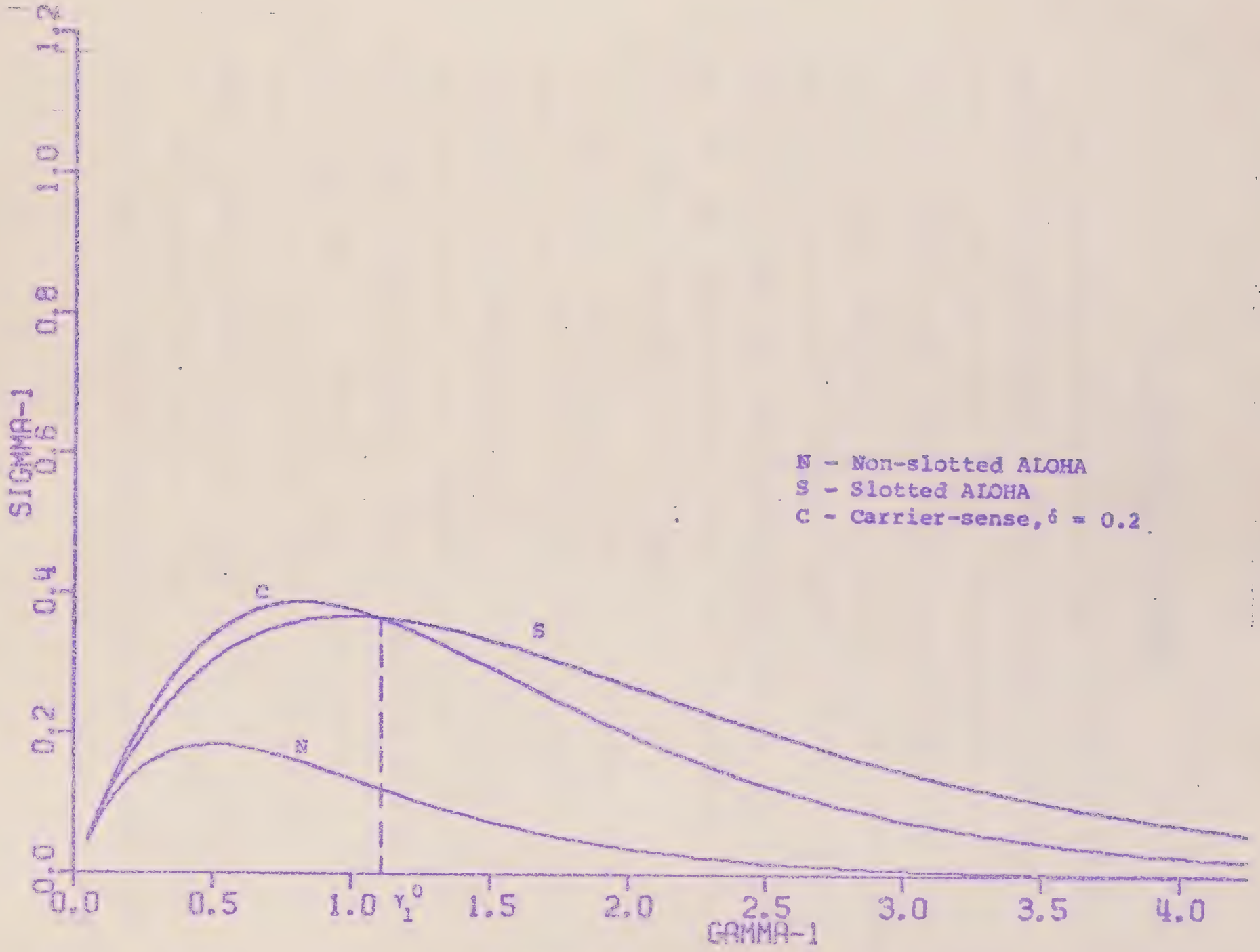

SIGMA-1
0.0
0.2
0.4
0.6
0.8
1.0
1.2
N - Non-slotted ALOHA
S - Slotted ALOHA
C - Carrier-sense, δ = 0.2
C
S
N
0.0
0.5
1.0 γ1°
1.5
2.0
2.5
3.0
3.5
4.0
GAMMA-1

FIGURE 8

IV. OTHER CONSIDERATIONS

The utilization obtained in this note includes the space overhead such as the packet header and the empty space when packets are not completely filled. The net utilization is therefore lower and the difference may become significant when the header size constitutes a relatively large part of the packet. Some of the configurations may be adaptable to multiple packet sizes in the sense that the packet utilization does not decrease when multiple packet sizes are used. The configurations have to be studied from this point of view.

When using a 2-channel configuration then packets from station to terminals do not collide with other packets. This feature may sometimes be desirable for purposes of labeling and control packets or other maintenance packets, or possibly for having a higher probability of successful transmission when responding to a query than when originating one. This, however, can be resolved in the 1-channel configurations by using a higher transmission power from station to terminals.

Let us depart for the moment from the model used in this note and consider a broadcasting system with several stages as described in [1]. In such a system it is possible to use direct

communication from terminal to terminal when a 1-channel configuration is used. In a 2-channel configuration at least one intermediate stage (repeater or station) is necessary.

When having a common channel it is possible to use echo acknowledgment so that the terminal can "hear" when its packet is repeated by the next stage. In the 2-channel case the terminal has to be specifically acknowledged; however echo acknowledgment can be used in the next stages. In fact, the 1-channel case has a disadvantage when using hop-by-hop acknowledgment packets since collisions may occur between the acknowledgment packet and the retransmission of that same packet which is acknowledges.

V. CONCLUSIONS

1. If we assume that α is not known and may be varying over a large range then we can classify the configurations into three classes: the inferior class includes configurations 1-N and 2-N, the intermediate class includes 2-S and 2-C, and the superior class includes 1-S and 1-C.

2. Assuming that α is not known then it would be recommended to use configuration 1-C or 1-S. These configurations are better than others over a large range of α. Even when α is known and one can split the channel for obtaining higher maximum utilization then there is a large interval of channel traffic for which the delay for the 1-channel configuration is lower than that for the 2-channel configuration for the same throughput. The advantage of the latter is only near the maximum utilization region. This case is demonstrated in Figure 4. It is noted that when $\alpha \to 0$ then 1-S behaves as a pure slotted ALOHA [3], and 1-C as a pure carrier-sense [2]; and when $\alpha \to \infty$ they behave as a point to point channel with an M /D/ 1 queuing system in which a throughput close to 1 can be obtained.

3. If α is known and the throughput is of more significance than the delay, then in such a case one can design a split

channel which results in a higher maximum utilization for configurations 2-S or 2-C. See for example Figures 4 and 5. In fact, if C is a given channel capacity to be split into C_1 and C_2 and a is known then C_1 and C_2 for which the maximum utilization is obtained satisfy:

$$C_1 + C_2 = C \tag{30}$$

$$\frac{C_2}{C_1} = a\sigma_{1M} \tag{31}$$

where σ_{1M} depends on the mode of channel access used.

4. An alternative configuration may be one in which one has n_1 channels from terminals to station and n_2 channels from station to terminals; however, with the possibility of trading between them when statistics about a are accumulated.

5. For the carrier-sense mode of channel access [2], it is suggested to investigate more accurate models, specifically: (i) to assume some distribution of terminals rather than having an average propagation time δ, and (ii) to wait a random time before an attempt to transmit a packet when the channel is sensed busy upon the arrival of the packet.

VI. REFERENCES

[1] Packet Radio-Systems Considerations; P.R.T.N.#5, Network Analysis Corporation, January 1, 1973

[2] L. Kleinrock and F. Tobagi: Throughput in Carrier-Sense (Autoslot) Packet Radio Systems; P.R.T.N.#24, February 12, 1973

[3] N. Abramson: The ALOHA System - Another Alternative for Computer Communications; 1970 Fall Joint Computer Conference, Vol. 37, pp. 281-285

[4] L. G. Roberts: Optimal Retransmission Delay for ALOHA System; ASS Note #9, July 3, 1972

[5] L. Kleinrock and S. S. Lam: Analytic Results with the Addition of One Large User; ASS Note #27, October 30, 1972

APPENDIX A

$\alpha = 0.5$

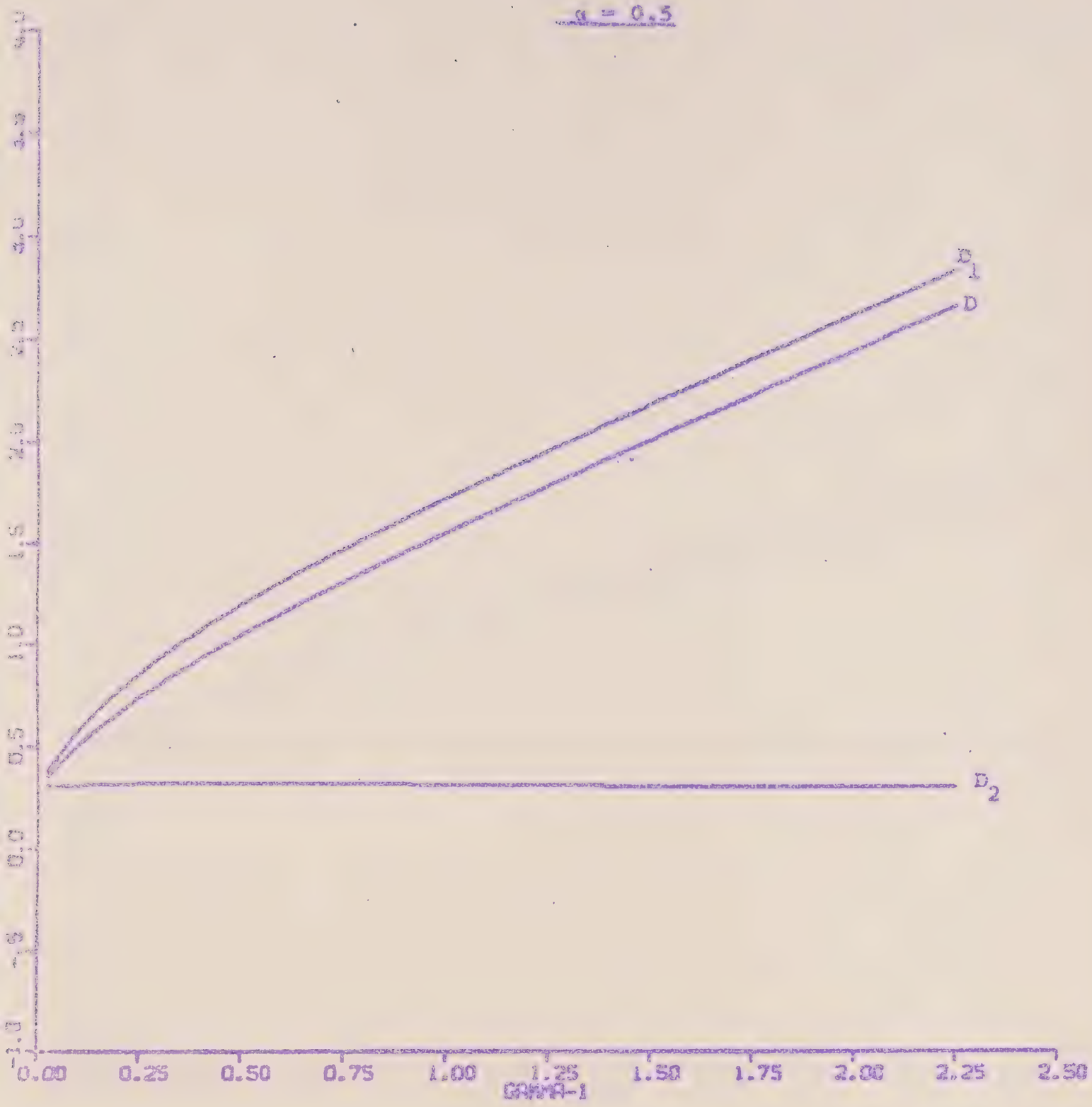


FIGURE A-2-N

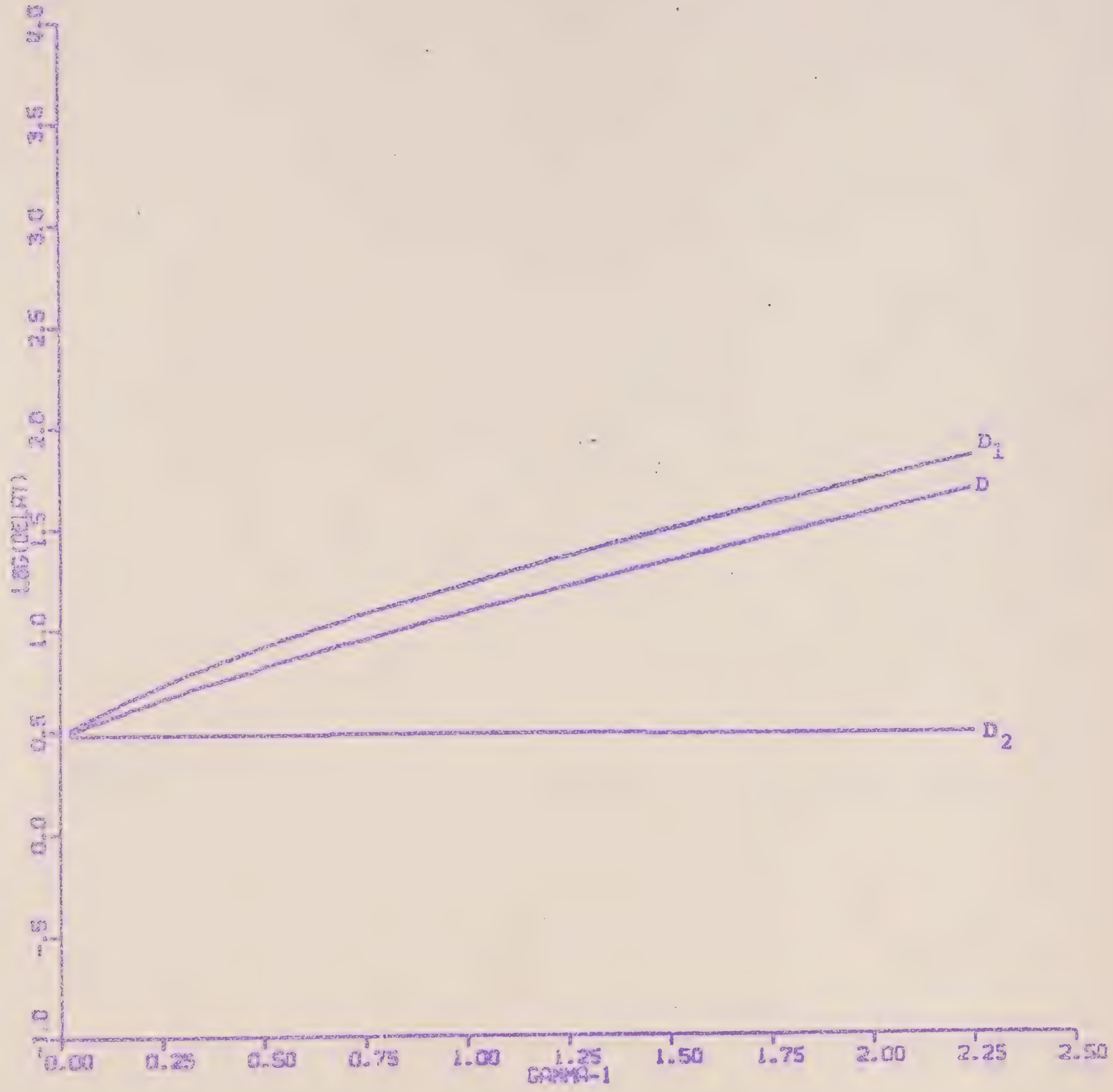

LOG(DELAY)
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
GAMMA-1
D1
D
D2

FIGURE A-2-S

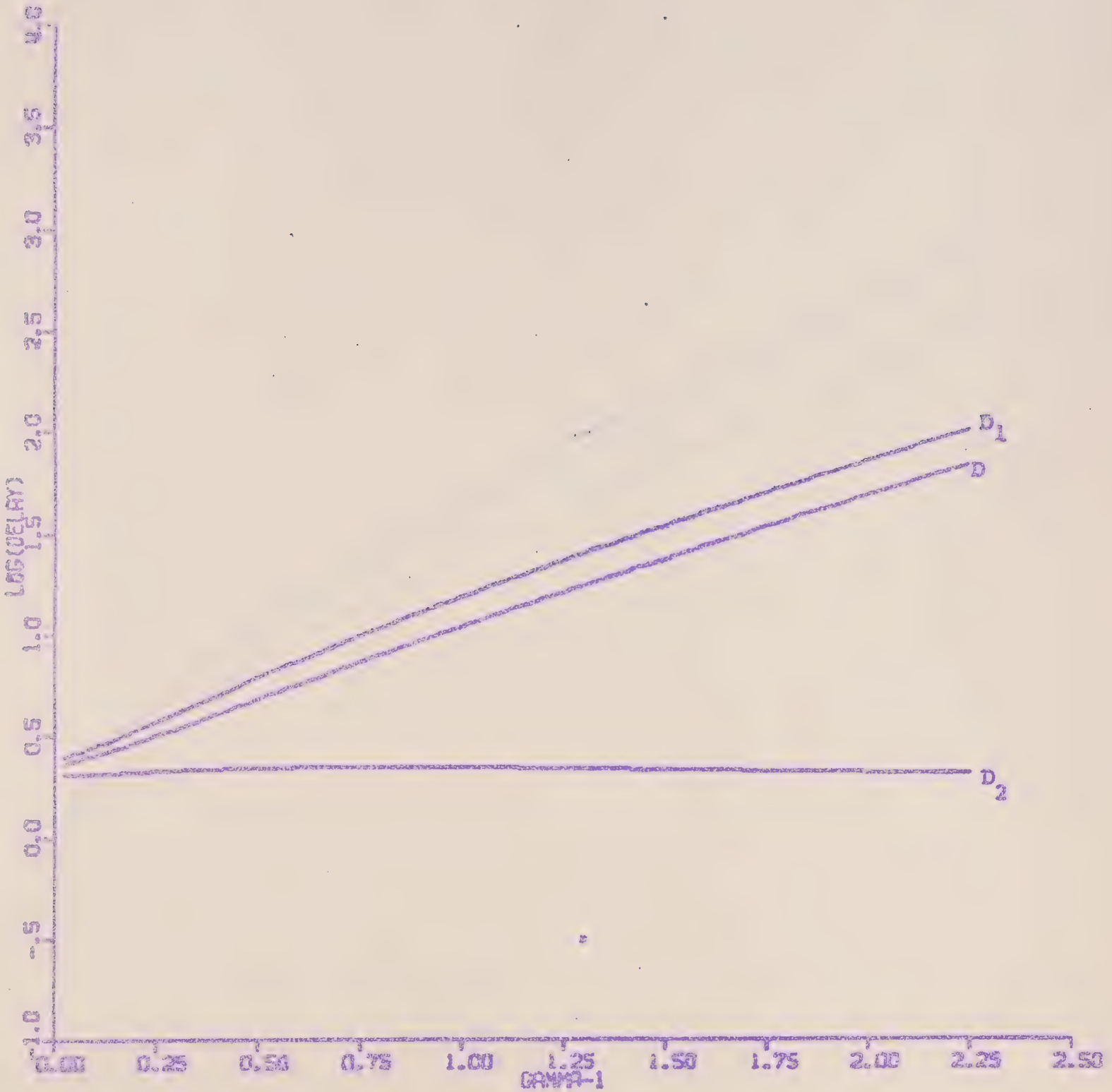

LOG(DELAY)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-.5
-1.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
GRAMS-1
D_1
D
D_2

FIGURE A-2-C

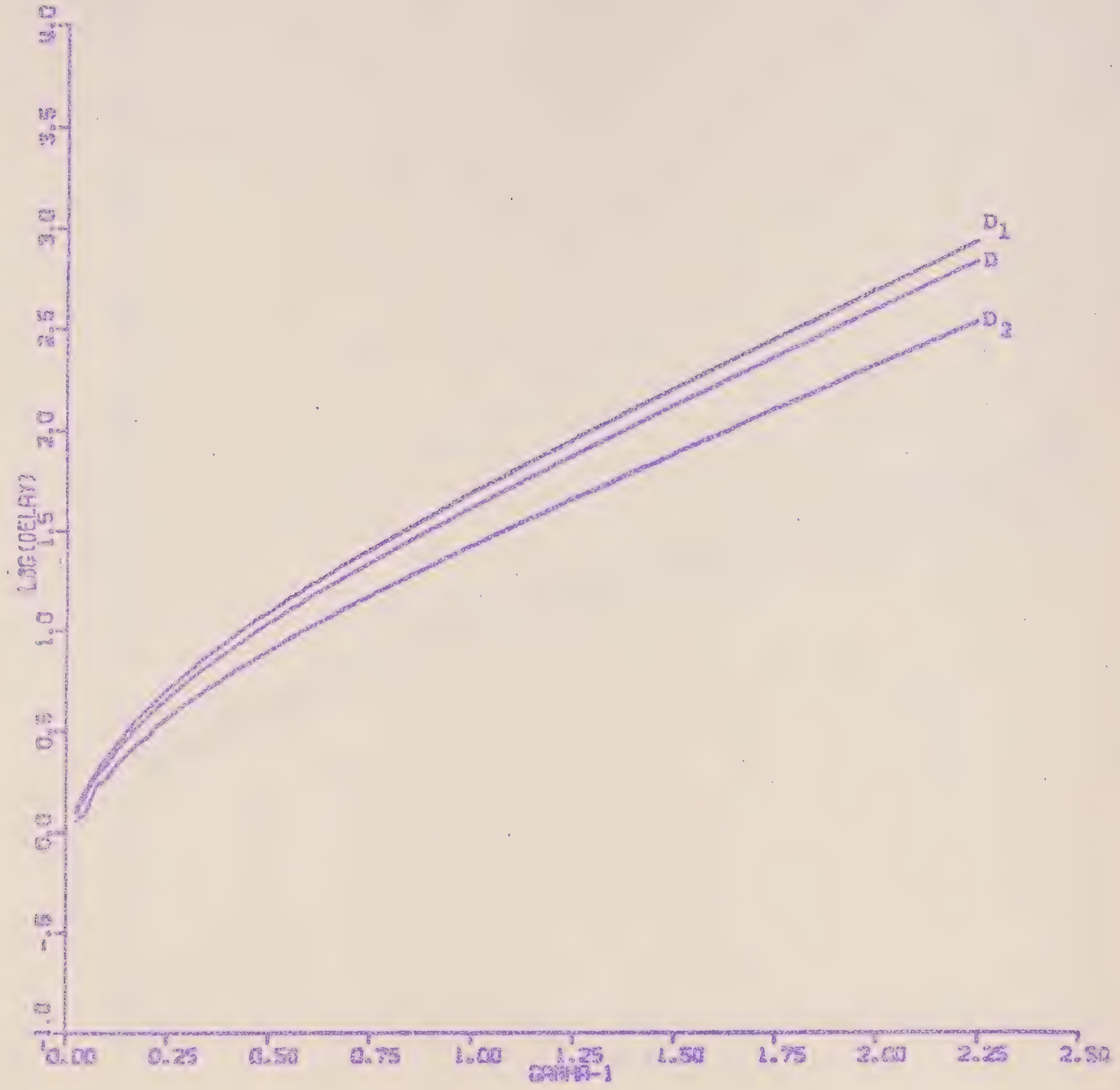

LOG(DELAY)
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
D1
D
D2
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
GAMA-1

FIGURE A-1-E

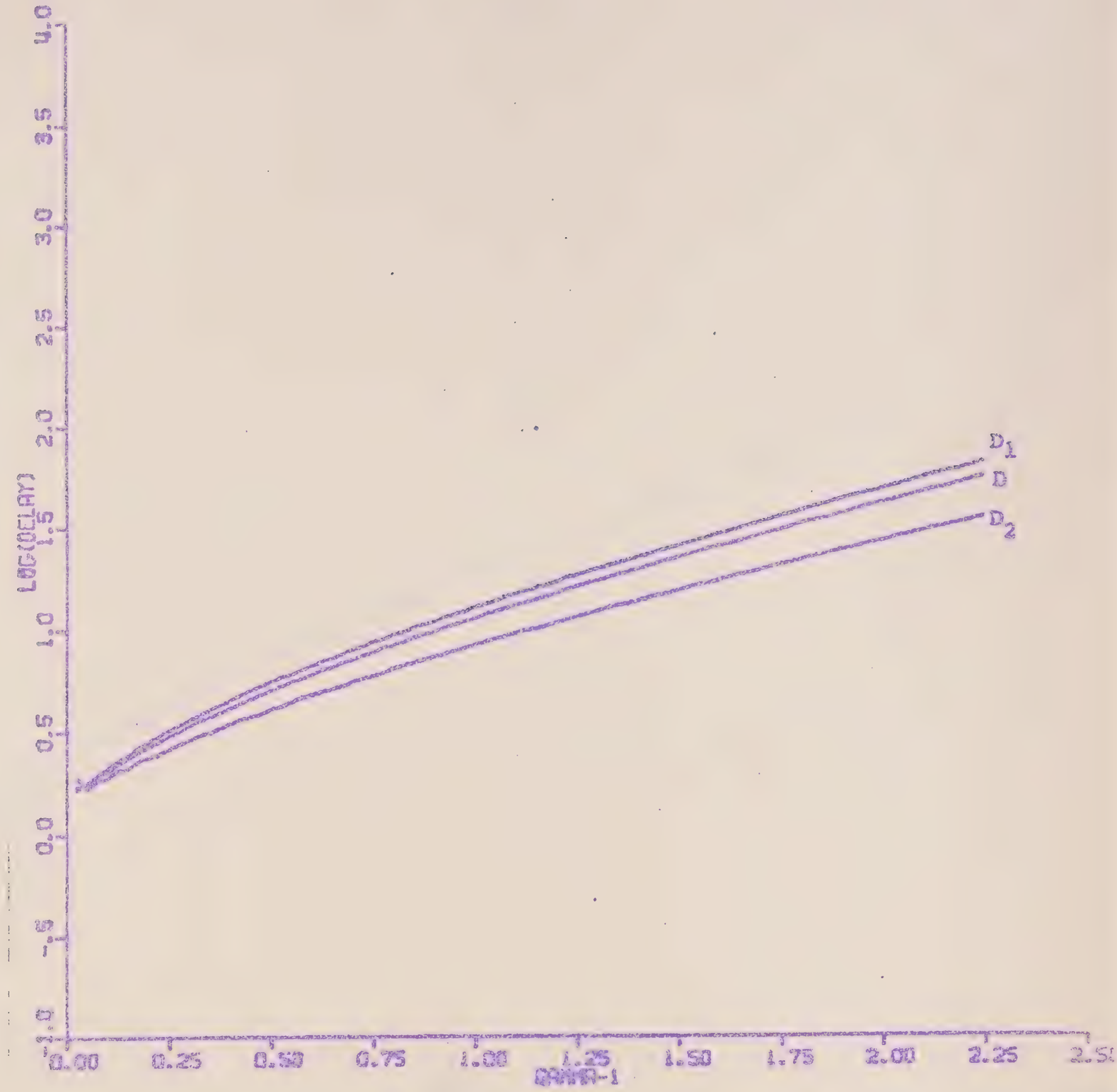

LOG(DELAY)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
D_1
D
D_2

FIGURE A-1-S

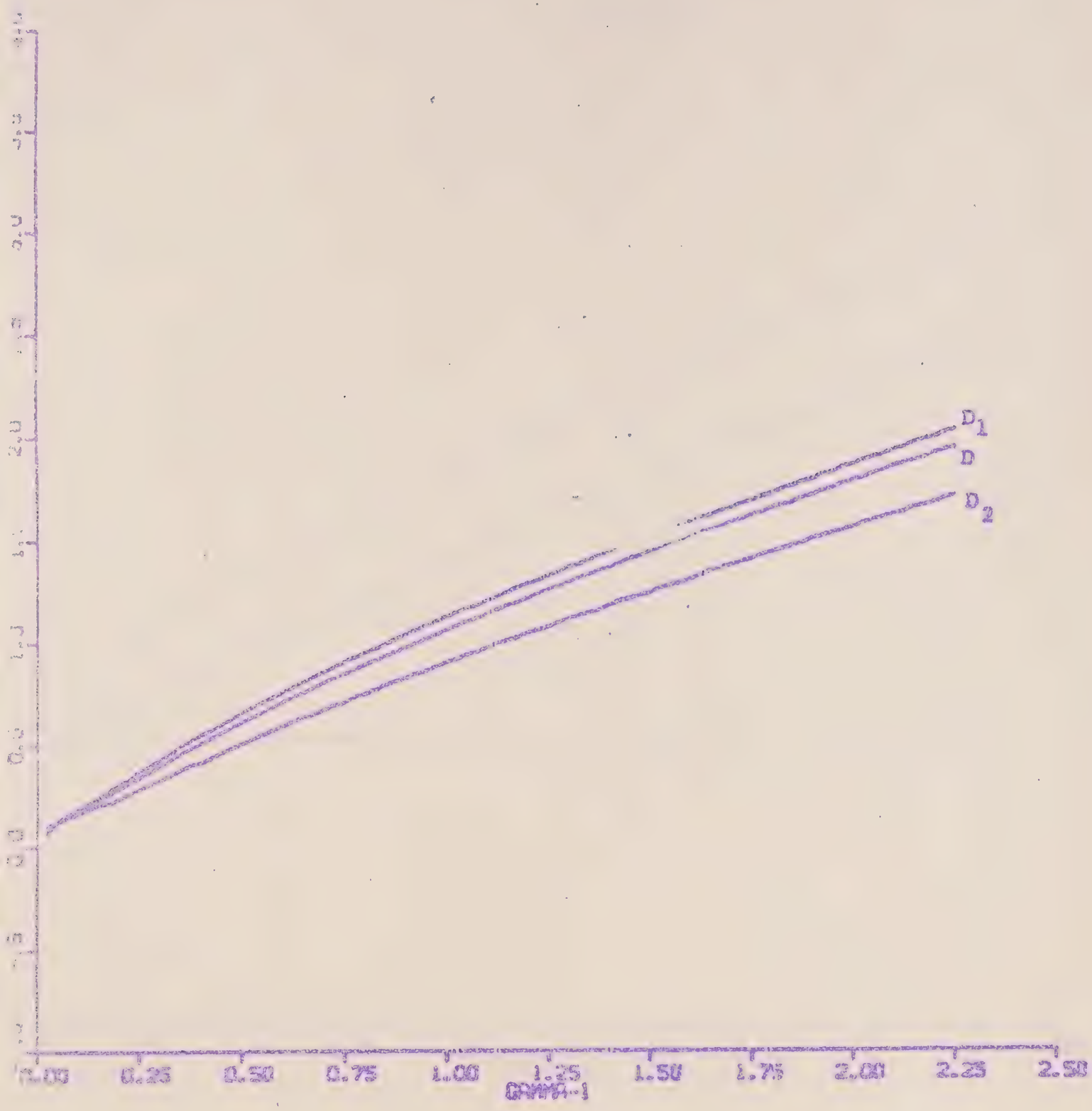


FIGURE A-1-C

APPENDIX B

$\sigma = 2.0$

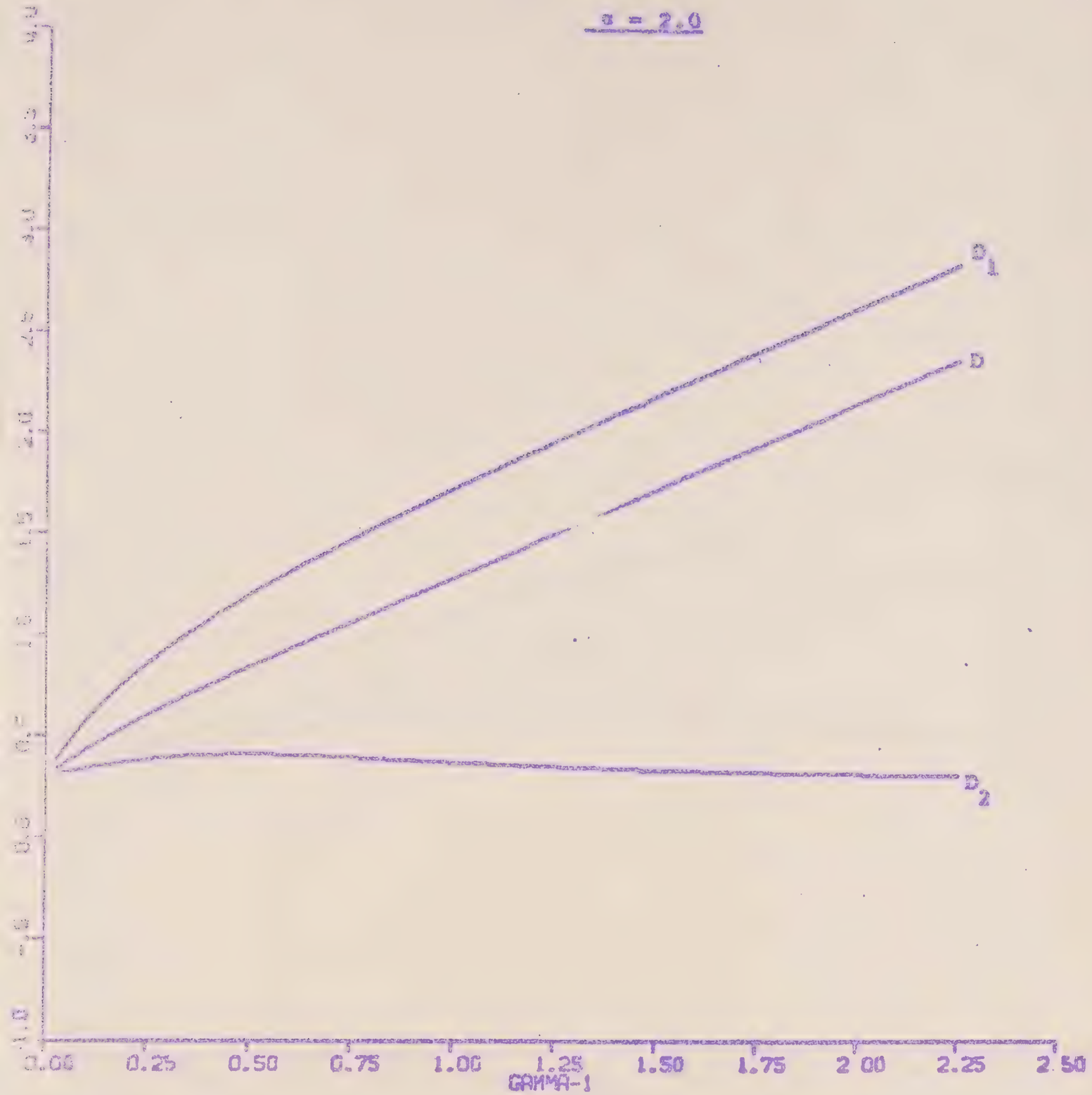


FIGURE B-2-N

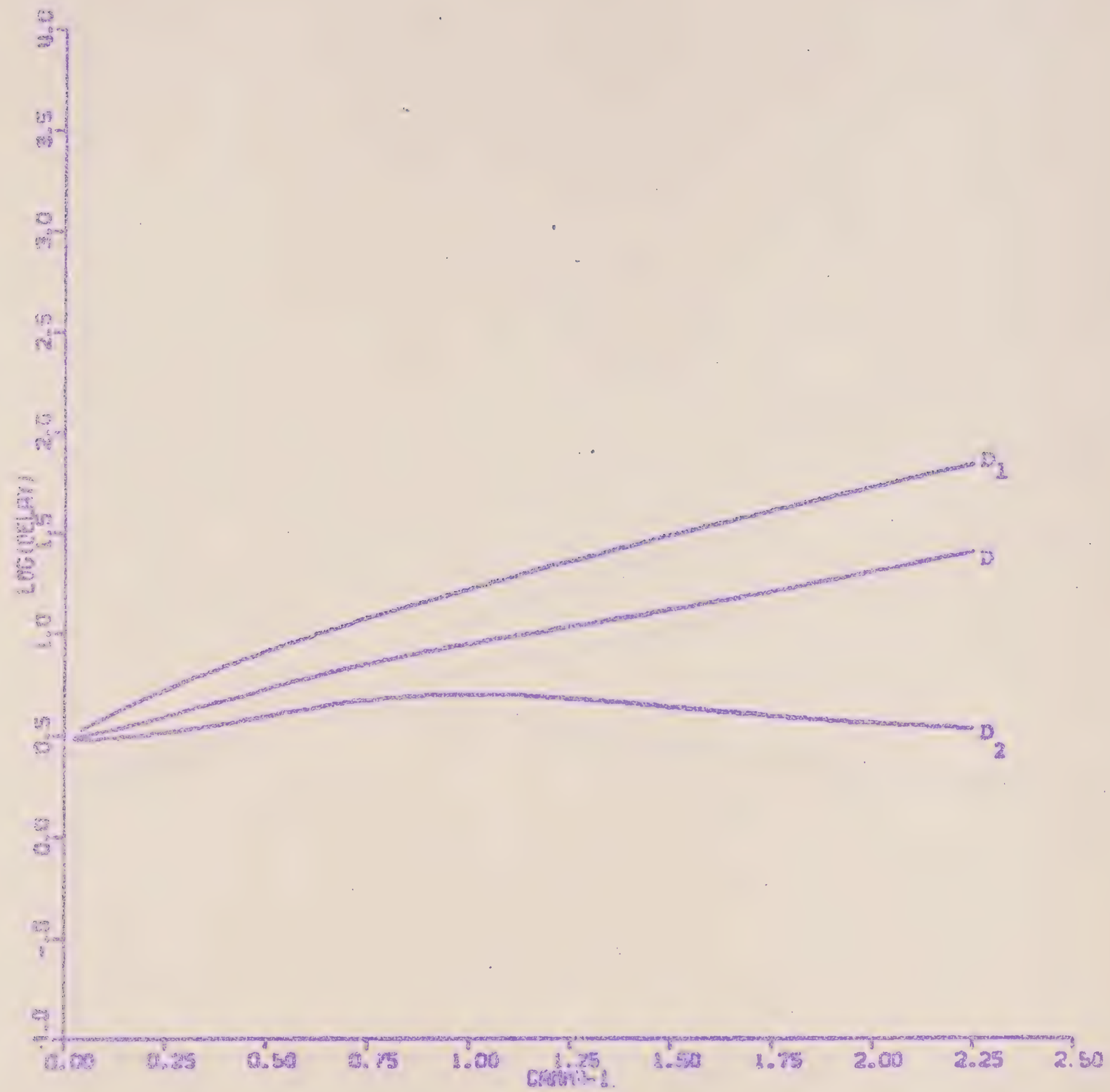
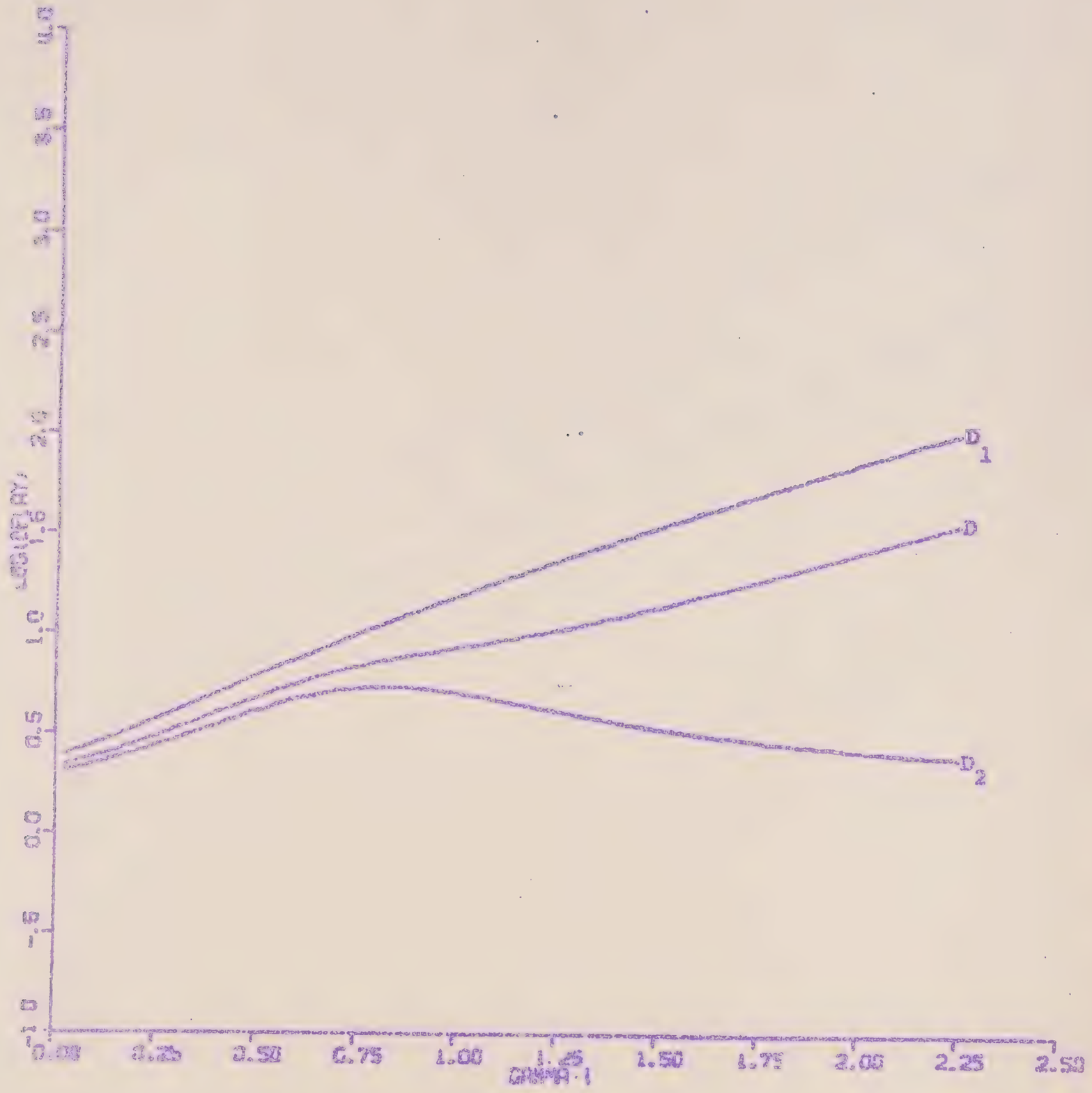
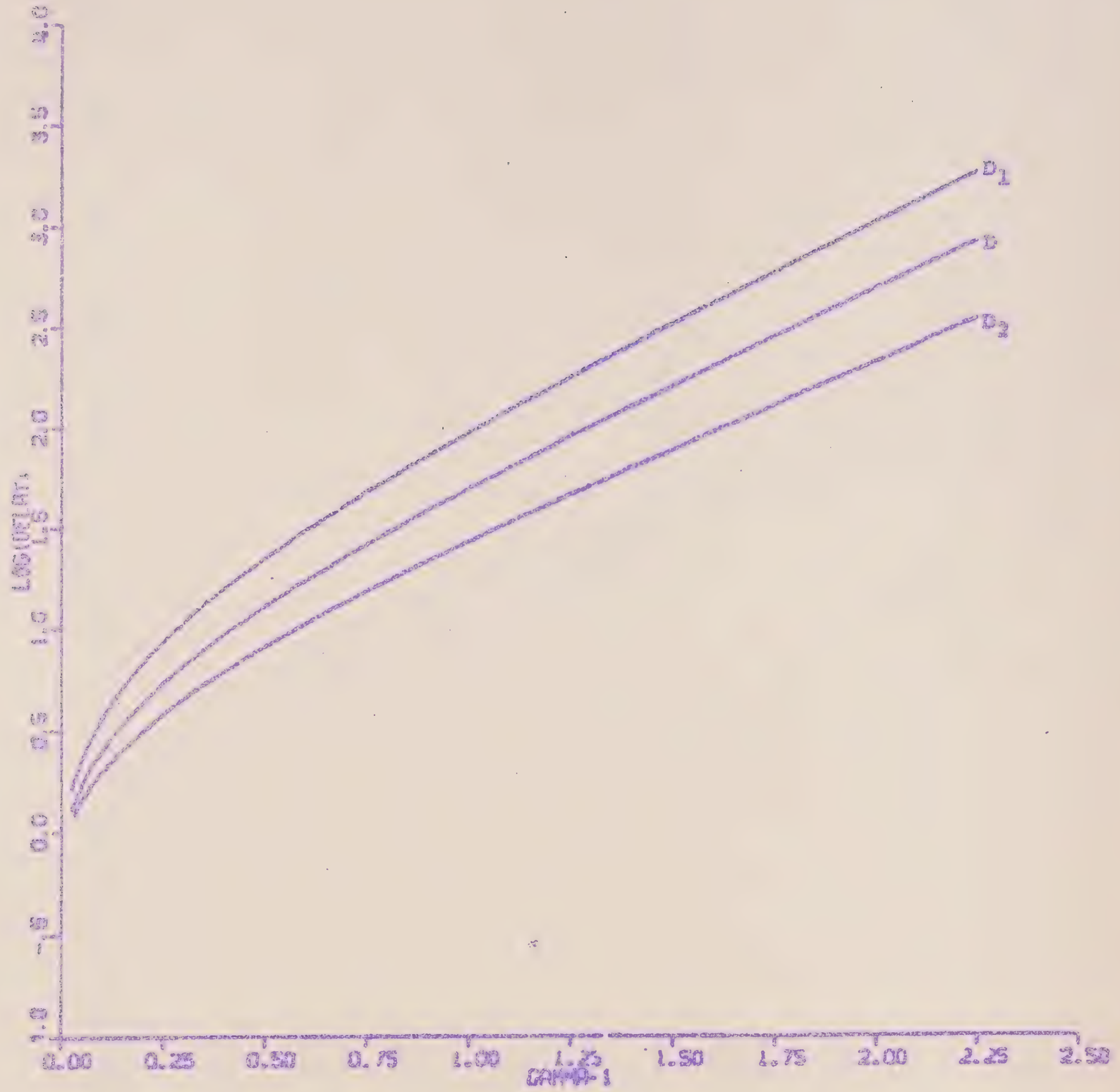

LOG(DELAY)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
D1
D
D2

FIGURE 3-2-5



LOG(DELAY)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-.5
-1.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
GAMMA-1
D_1
D
D_2

FIGURE B-2-C



LOG(DELAY)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-.5
-1.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
GAMMA-1
D_1
D
D_2

FIGURE B-1-N

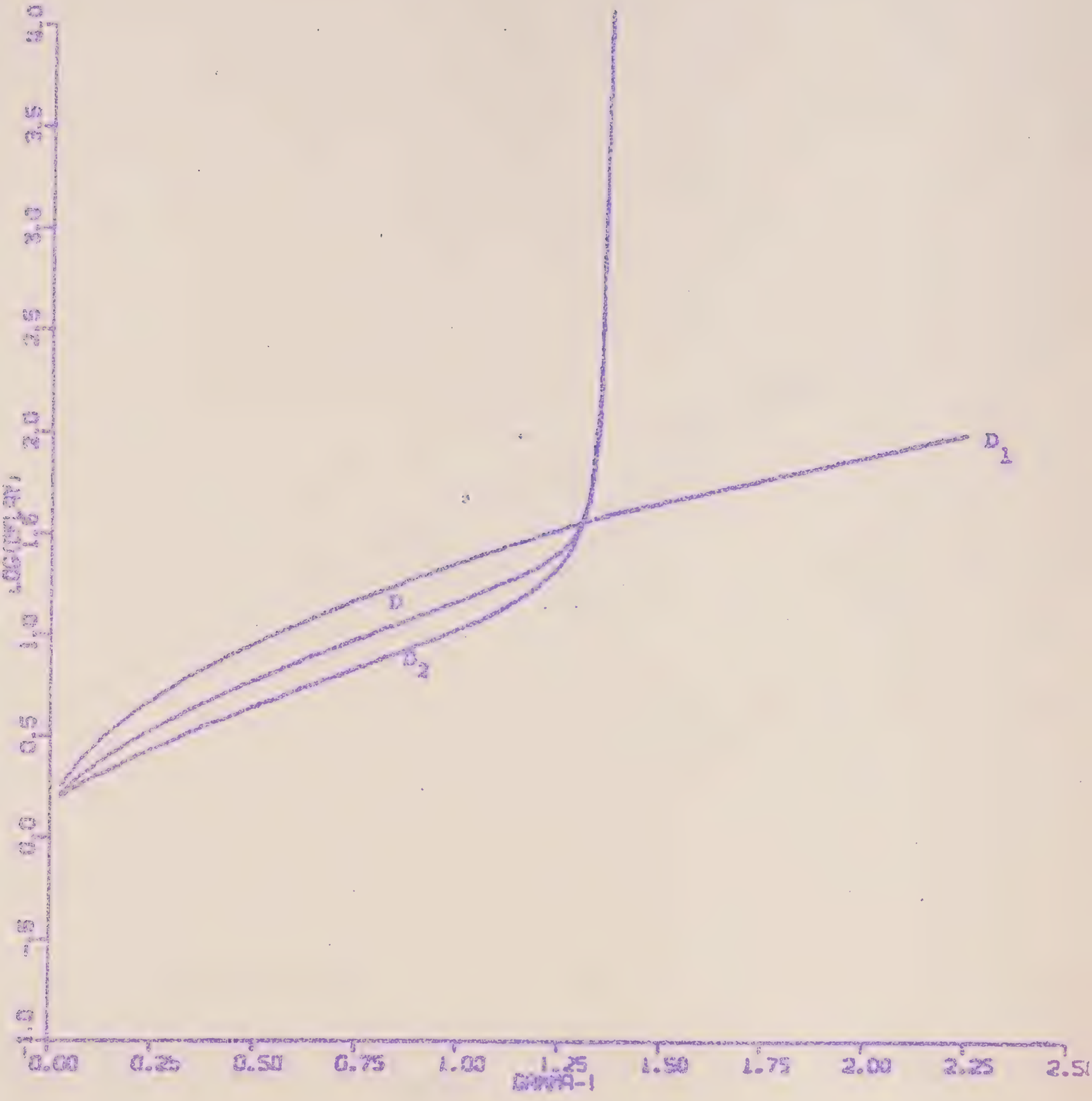


FIGURE B-1-S

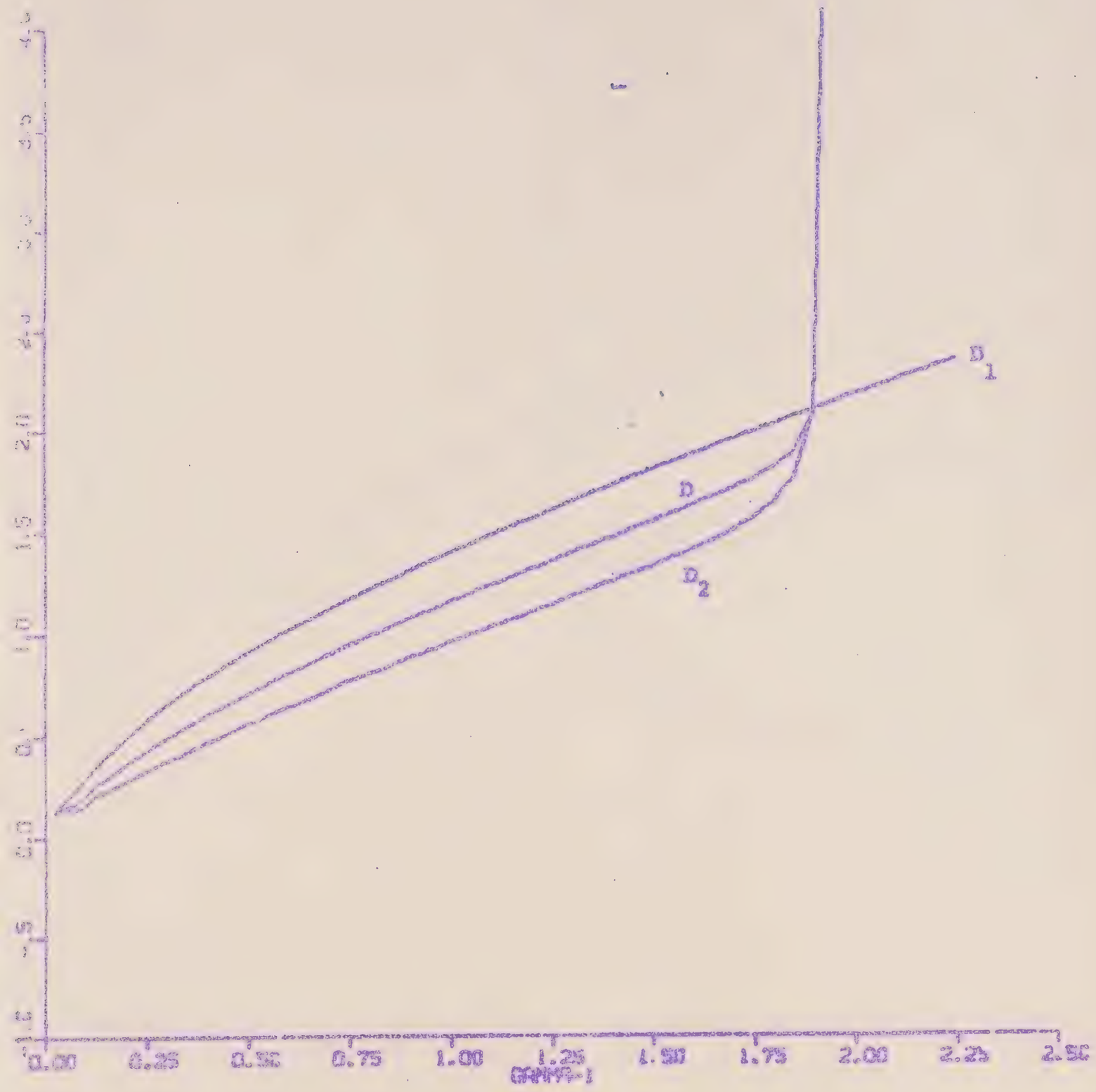


FIGURE B-1-C

APPENDIX C

a = 10.

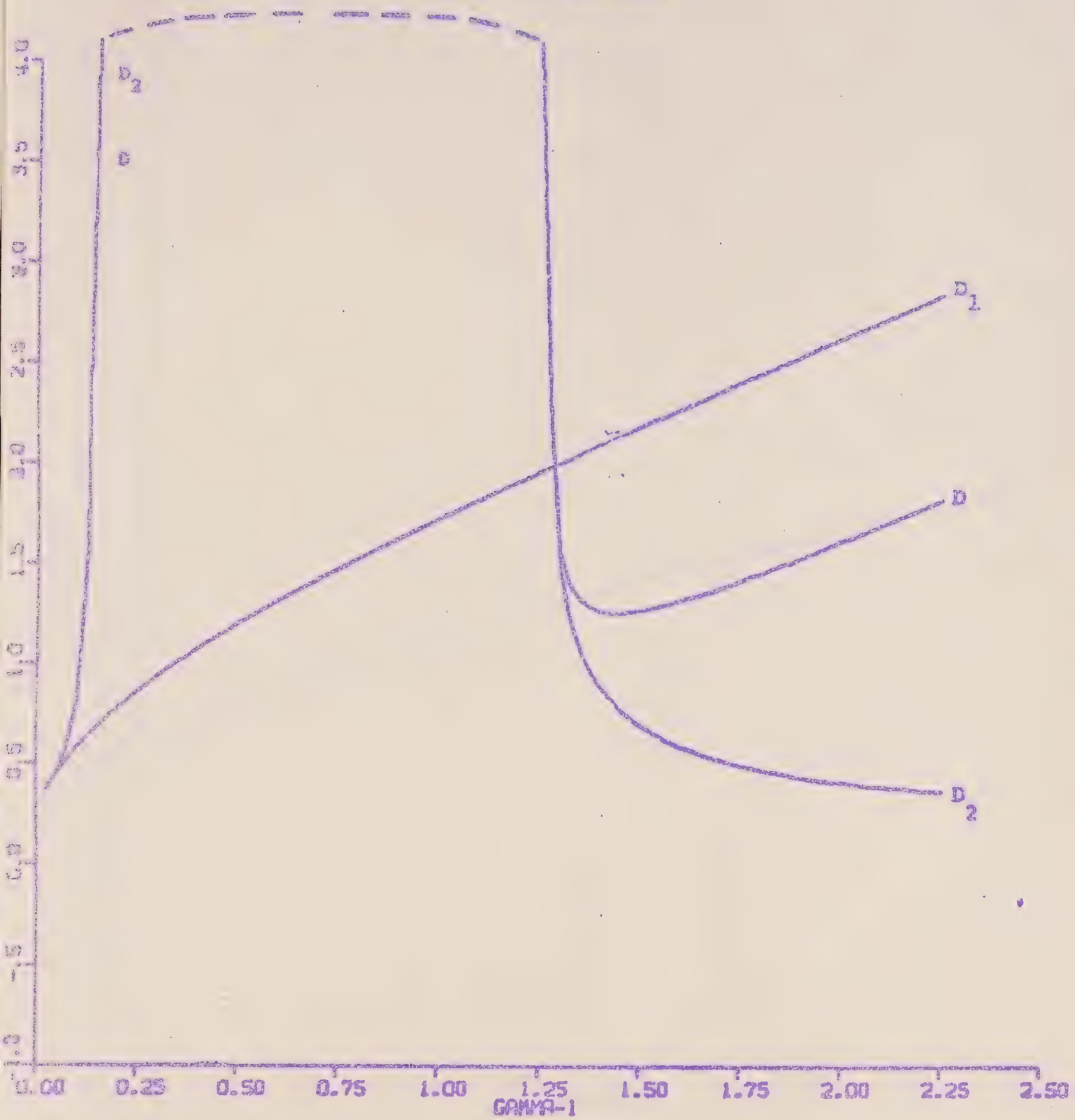


FIGURE C-2-N

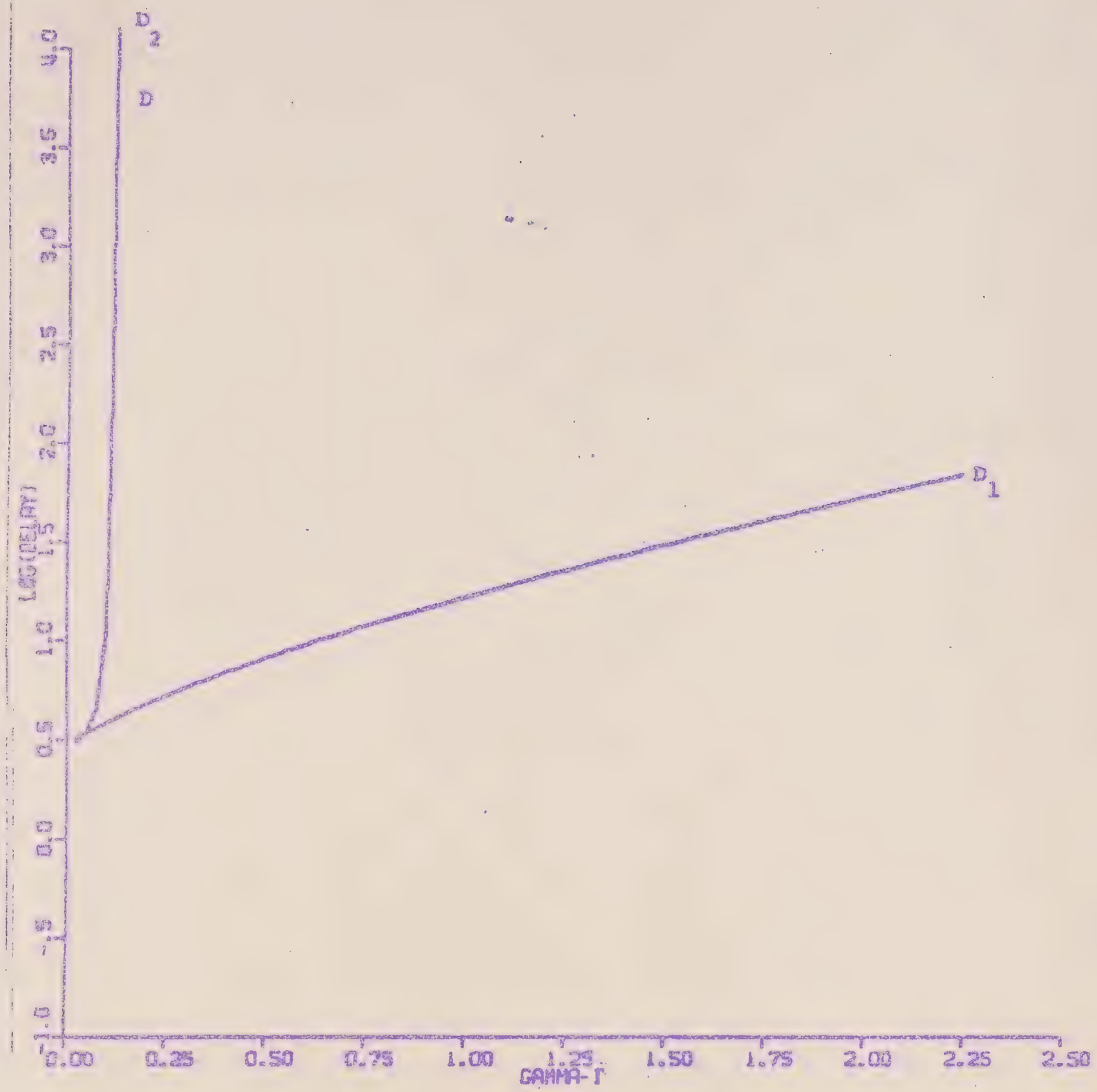
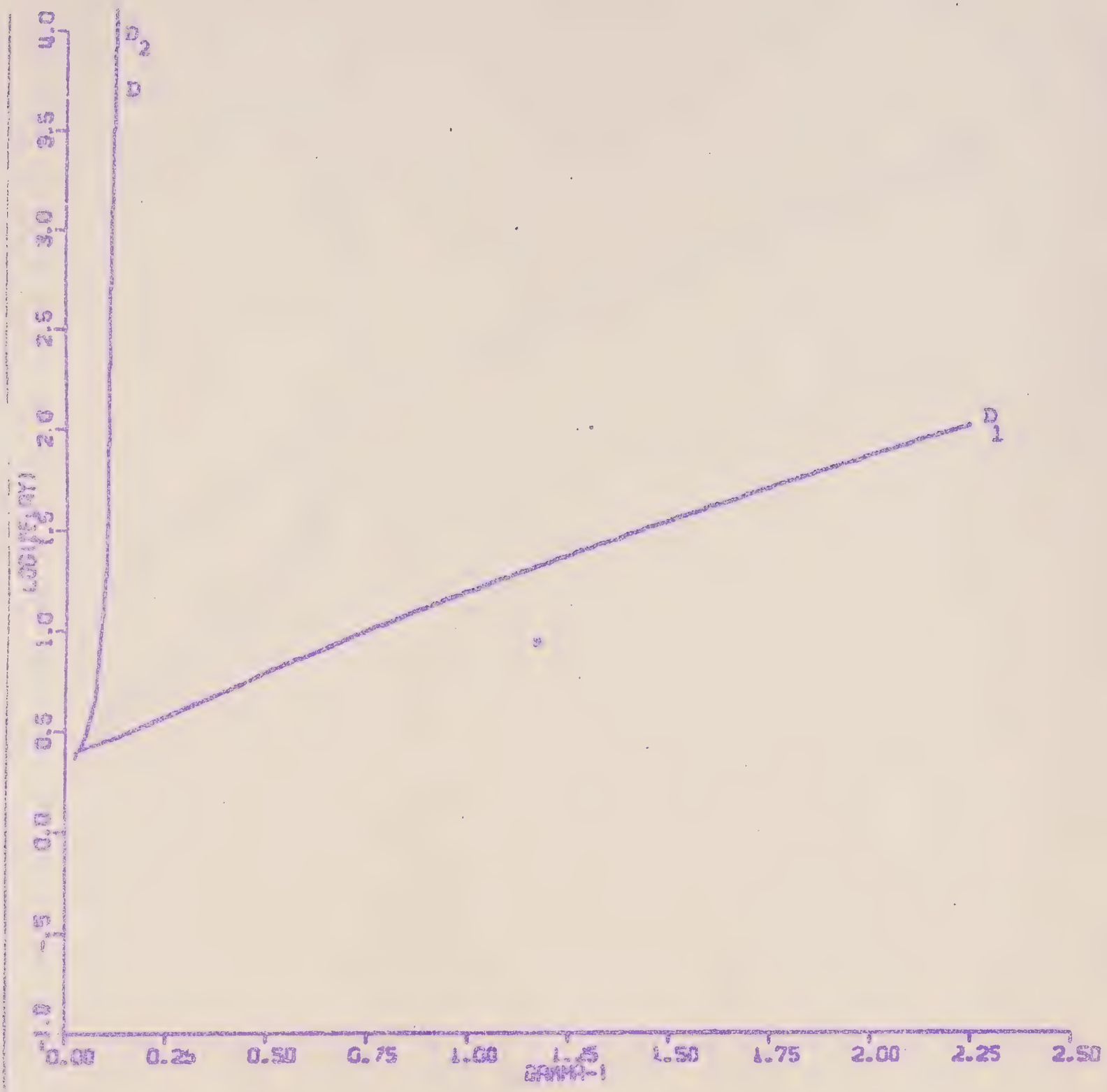

D2
D
D1
LOG(DELAY)
-.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
GAMMA-1

FIGURE C-2-6



D2
D
D1
LOG(FLAY)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-.5
-1.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
GAMMA-1

FIGURE C-2-C

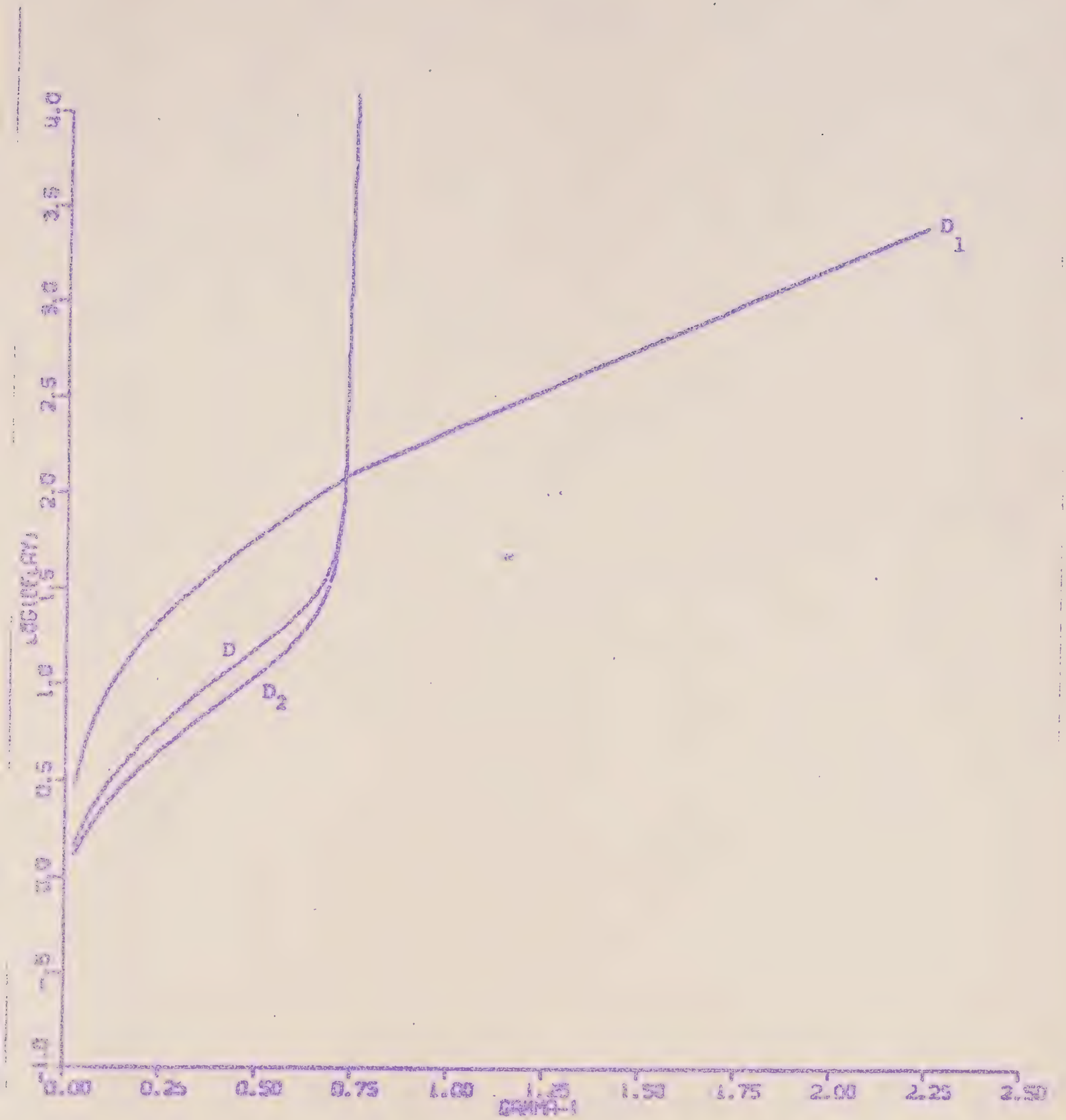

D
1
D
D
2
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50

FIGURE C-1-N

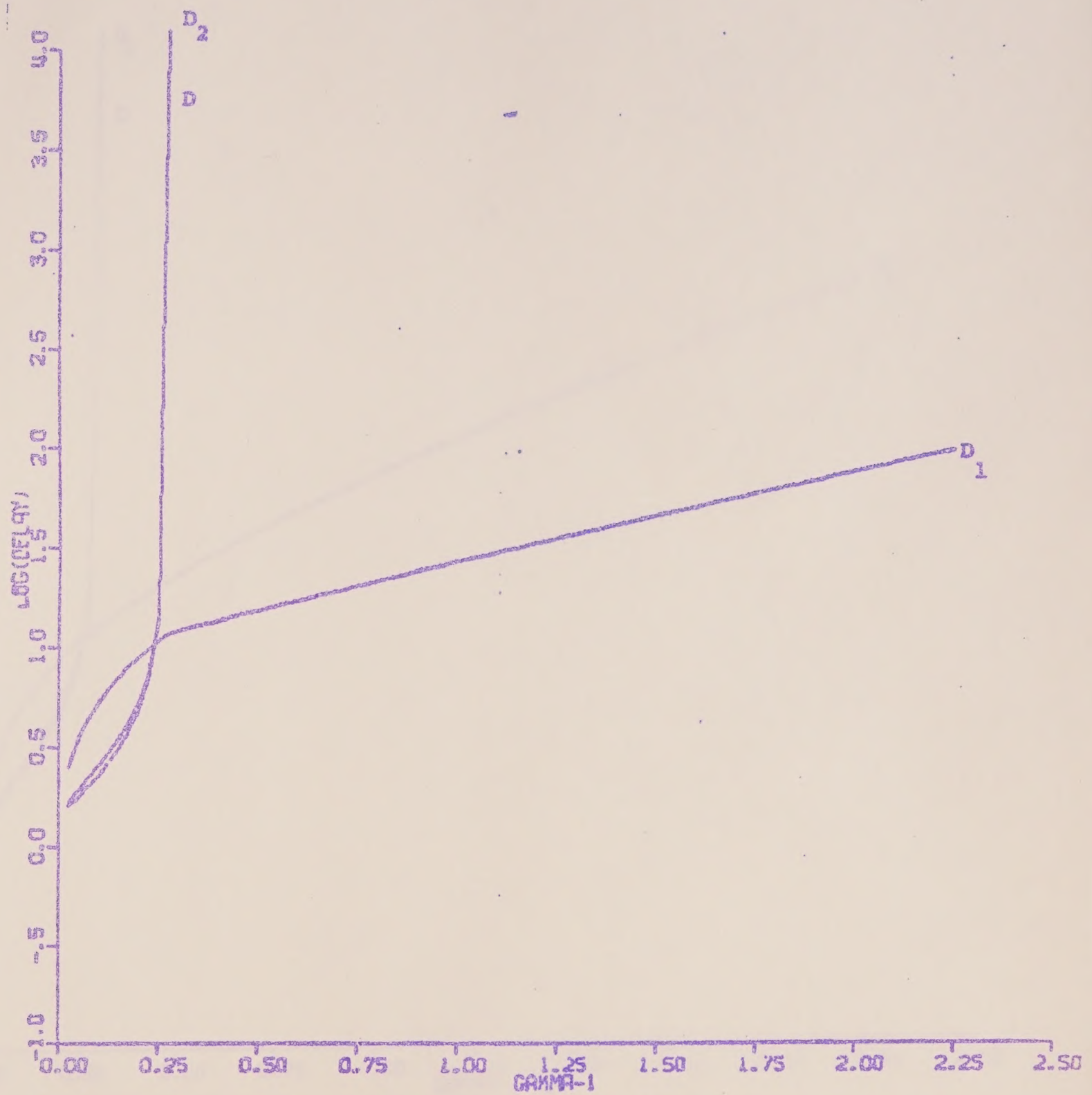

D2
D
D1
LOG(DELTA)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-.5
-1.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
GAMMA-1

FIGURE C-1-S

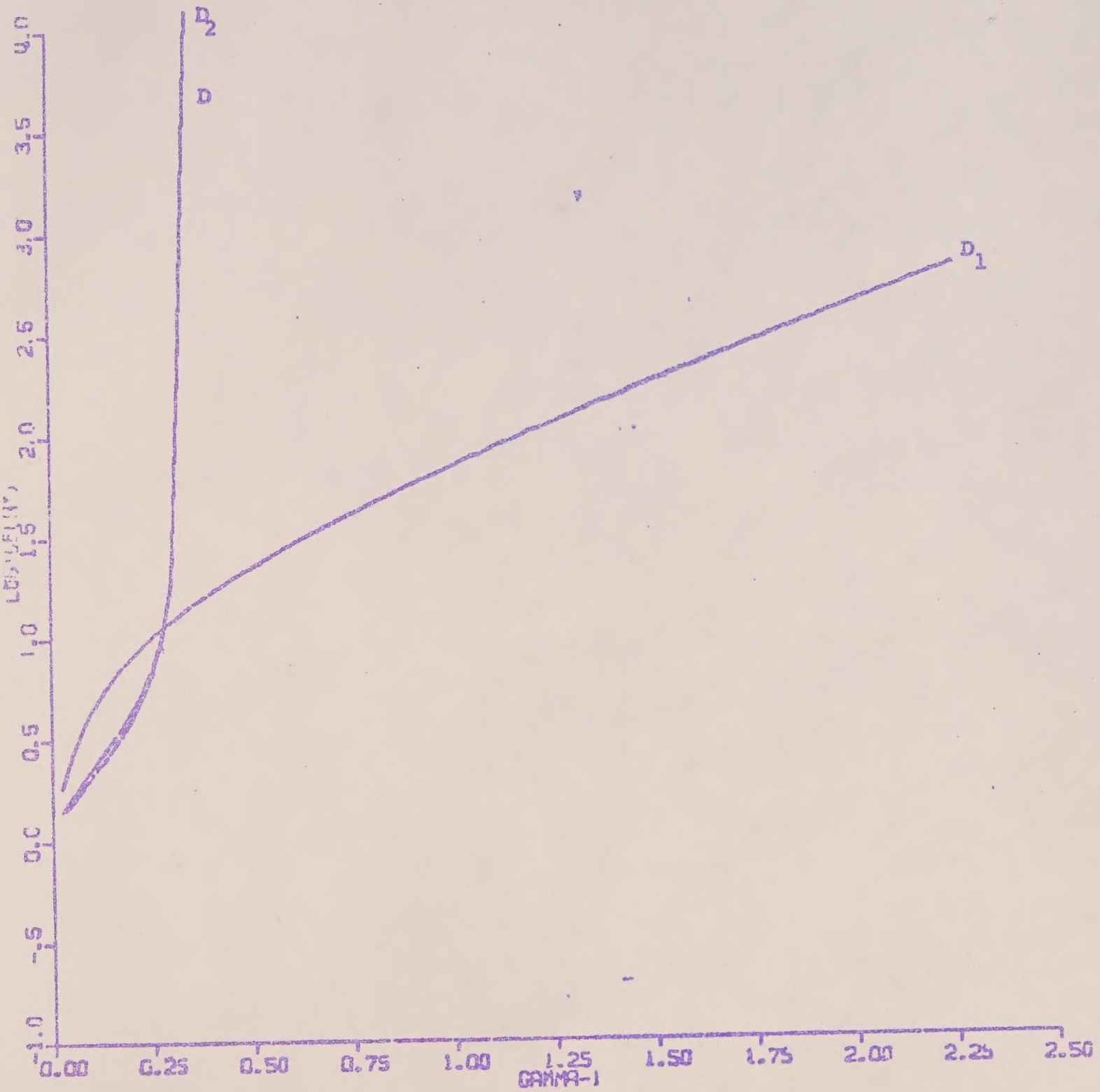

D2
D
D1
-1.0
-.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
GAMMA-1

FIGURE C-1-C

D'
A